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HIGH-PRESSURE PERFORMANCE OF COMBUSTOR SEGMENTS UTILIZING PRESSURE-ATOMIZING FUEL NOZZLES AND AIR SWIRLERS FOR PRIMARY-ZONE MIXING

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16. Abstract

Three rectangular combustor models, 0.457 m (18 in.) long with maximum cross sections of 0.153 by 0.305 m (6 by 12 in.), were tested at high inlet-air pressures. Test conditions included: inlet-air pressures of 10 to 26.7 atmospheres, inlet-air temperatures of 355 to 756 K (640° to 1360° R), reference velocities of 16 to 36.6 m/sec (52.5 to 120 ft/sec), and fuel-air ratios of 0.005 to 0.022. Increasing the inlet-air pressure increased the smoke number, pattern factor, and liner temperature. High combustion efficiency and smoke numbers below the visible limit were obtained with combustors designed for relatively high airflow through axial swirlers.

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HIGH-PRESSURE PERFORMANCE OF COMBUSTOR SEGMENTS UTILIZING PRESSURE-ATOMIZING FUEL NOZZLES AND AIR SWIRLERS FOR PRIMARY-ZONE MIXING

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SUMMARY

In order to relate methods of primary- and secondary-zone mixing to combustor performance at high inlet-air pressures, comparisons were made of three rectangular short-length combustor segments using four types of air swirlers and burning ASTM A-1 fuel. The rectangular combustor had a cross section of 0.053 by 0.305 meters (2.1 by 12 in.) at the diffuser inlet, 0.051 by 0.305 meter (2 by 12 in.) at the combustor exit, and a maximum combustor cross-section of 0.153 by 0.305 meter (6 by 12 in.). Each of the three combustors was 0.457 meter (18 in.) long, which included the diffusers, and a snout open-area of either 20 or 40 percent was used to capture air for the swirlers. Both external scoops and internal chutes were used for secondary-zone mixing.

Test conditions included: inlet-air total pressures of 10 to 26.7 atmospheres, a fuel-air ratio range of 0.005 to 0.022, inlet-air total temperatures of 355 to 756 K (640° to 1360° R), and reference velocities of 16 to 36.6 meters per second (52.2 to 120 ft/sec). Combustion efficiencies at pressures of 10 to 20 atmospheres were approximately 100 percent for the two combustors in which relatively high airflow was captured by the snout. Pattern factors increased with increasing fuel-air ratios, inlet-air total pressures at high fuel-air ratios, and swirler axial velocity-ratios.

Exhaust smoke number increased with increasing inlet-air pressure and decreased with increasing fuel-air ratios, inlet-air total temperatures, and reference velocities. Low smoke numbers (<6) were obtained with the 55° axial and the dual-concentric types of air swirlers. High combustion efficiencies and low smoke numbers indicated that fairly rapid primary- and secondary-zone mixing was achieved by passing high airflow through either 55° axial or dual-concentric types of air swirlers.

INTRODUCTION

The development of high-compressor-ratio turbojet engines represents an important advance in current aircraft design (ref. 1). As a result of higher compressor ratios, combustors are required which will be durable and perform well at high inlet-air pressures and temperatures. In the present investigation, the primary objective was not as much to obtain high performance as it was to determine the effect of increased inlet-air pressure on combustor characteristics such as smoke formation and liner temperatures. Smoke formation and radiance data, which were the primary results of the overall investigation, are described in more detail in reference 2.

Although the three combustors used in this study had burning lengths of only 0.32 meter (12.5 in.), the attainment of short length was not a primary objective. Thus, no attempts were made to improve combustor characteristics such as pattern factor and blow-out limits which did not meet requirements for some aircraft applications. In reference 3, a short length swirl-can combustor, 0.29 meter (11.4 in.) long, was reported to give good performance, and in reference 4 a short length side-entry combustor, 0.36 meter (14 in.) long, also gave good results.

In operating short-length combustors at high inlet-air pressures, one of the main requirements is rapid primary- and secondary-zone mixing of fuel and air. Rapid mixing is needed to obtain high heat-release rate per unit volume and a uniform exit temperature profile and also to avoid the generation of locally rich zones that produce excessive exhaust smoke. Besides being an air pollution problem, generation of smoke in the combustor tends to increase the radiant heat-transfer rate from the flame to the combustor liner (ref. 2). As a result, combustor durability is decreased when excessive smoke formation occurs, particularly at elevated inlet-air pressures.

One of the methods of fuel-air mixing that is often used in contemporary combustor design use pressure-atomizing fuel nozzles and air swirlers. This approach was used at high inlet-air pressures in the present study. Rectangular combustor segments were designed that divided the airflow at the combustor inlet with a substantial portion of the air captured by the snout and passed through the air swirlers. Thus, the relation of swirler airflow-rates to combustor performance was studied at high inlet-air pressures with pressure-atomizing fuel nozzles and four different types of air swirlers.

Secondary-zone mixing is also very important in the design of high-efficiency, short-length combustors to operate at high inlet-air pressures. A recent investigation of exit temperature profiles for short-length combustors has shown that rapid secondary-zone mixing was obtained with three different types of dilution-air entry apertures (ref. 5). Results from the study were used in the design of liners for the three combustors tested in the present investigation.

Also included in this investigation of high inlet-air pressure effects was a comparison of the performance of three short-length combustor segments using pressure

atomizing fuel nozzles, four types of air swirlers, and burning ASTM A-1 fuel. To evaluate performance, the following combustor characteristics were determined: combustion efficiency, total pressure loss, exit temperature profile, pattern factor, exhaust smoke number, combustor liner temperature, and blowout data. Other factors considered were the effect of inlet-air total temperature, reference velocity, and fuel-air ratio on combustor characteristics. Also, the variation of pattern factor with the dimensionless axial-velocity ratio of the three types of air swirlers was investigated.

APPARATUS AND PROCEDURE

Test Facility

The test combustor was mounted in a closed-duct test facility shown in figure 1, and tested at inlet-air pressures up to 26.7 atmospheres and temperatures up to 922 K (1660° R). Combustion air drawn from the laboratory high-pressure supply system was

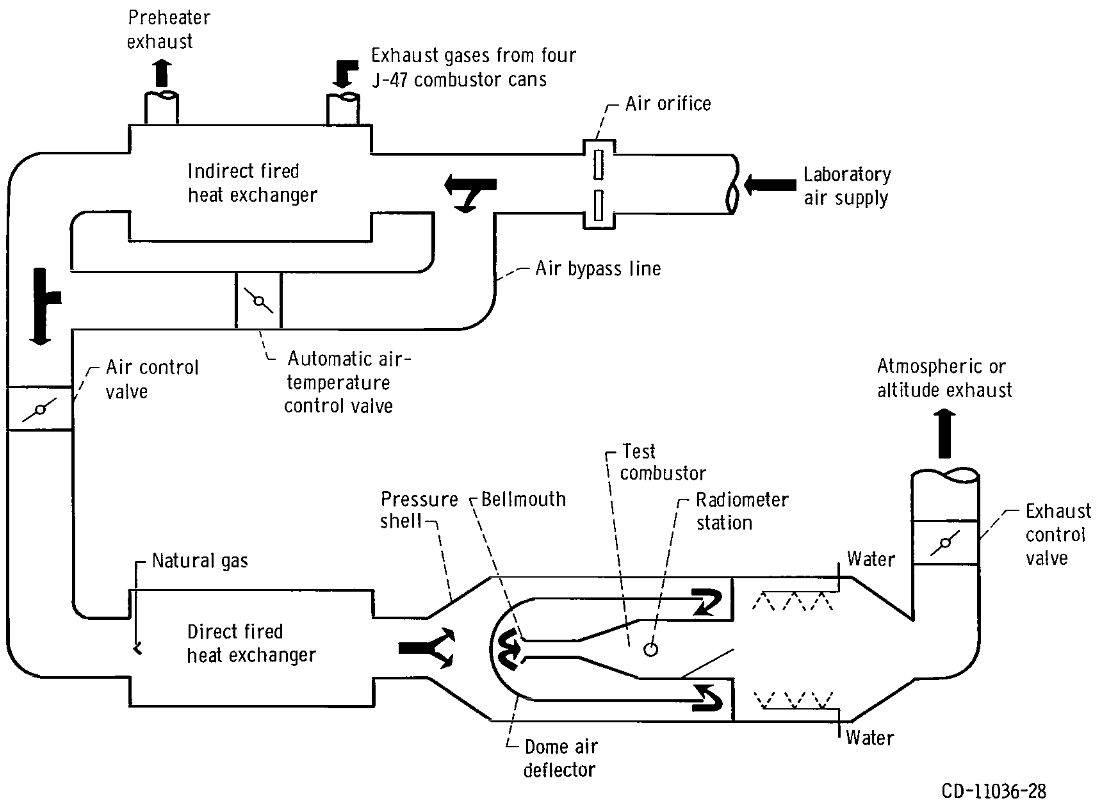


Figure 1. - Test facility and auxiliary equipment.

indirectly heated up to 589 K (1060° R) in a counter flow U-tube heat exchanger.

The temperature of the air flowing out of the heat exchanger was automatically controlled by mixing the heated air with varying amounts of cold bypassed air. To obtain temperatures above 589 K (1060° R), the air was further heated with a natural-gas vitiating heater mounted downstream of the heat exchanger. Airflow through the heat exchanger and bypass flow system and the total pressure of the combustor inlet airflow were regulated by remote control valves.

Test Section

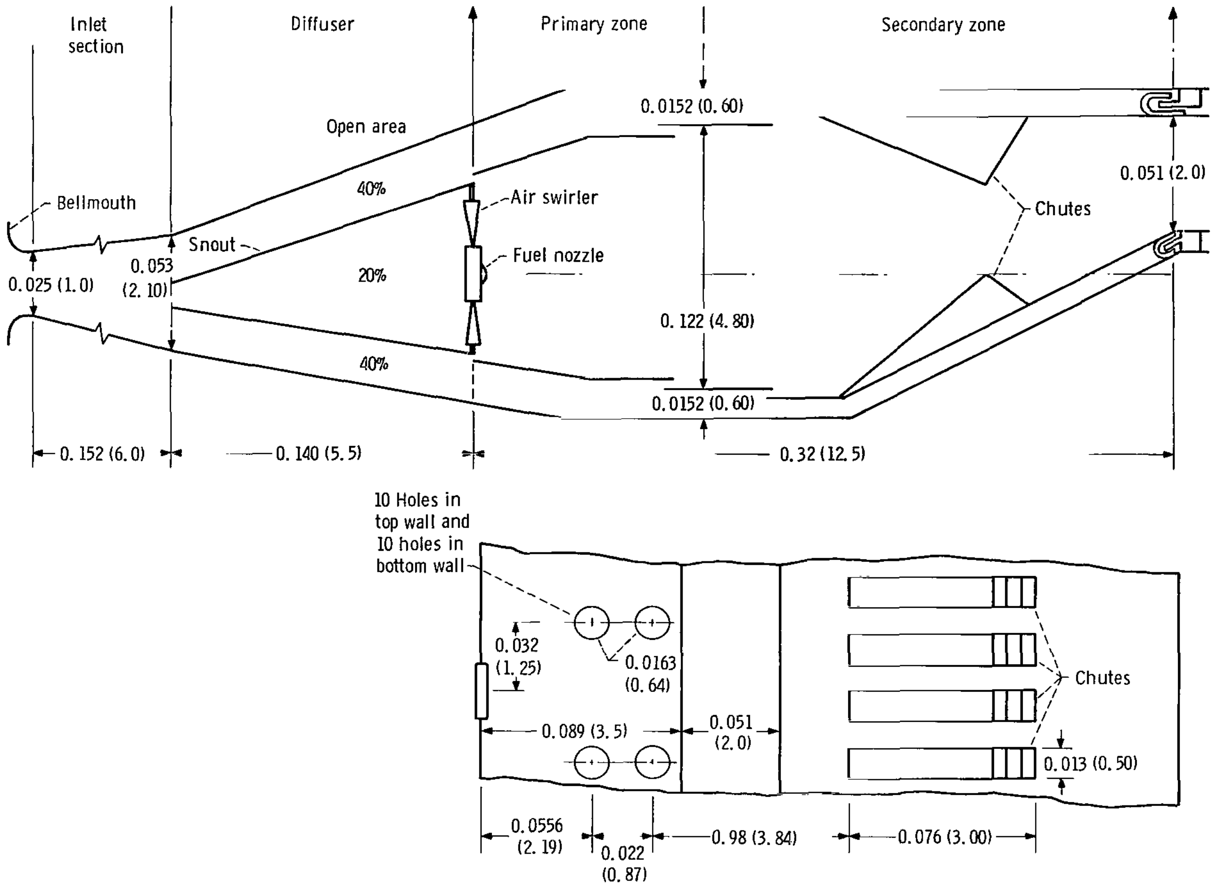
The combustor was mounted in the counterflow high-pressure test section as shown in figure 1. This counterflow arrangement was a safety precaution which, in the event of a fuel leak, prevented an accumulation of fuel in the housing. Combustion air flowed through the outer annular passage, back through the inner annular passage surrounding the combustor, and was finally deflected by the dome back through the combustor. A bellmouth upstream of the combustor gave a uniform airflow distribution at the diffuser inlet.

Test Combustor

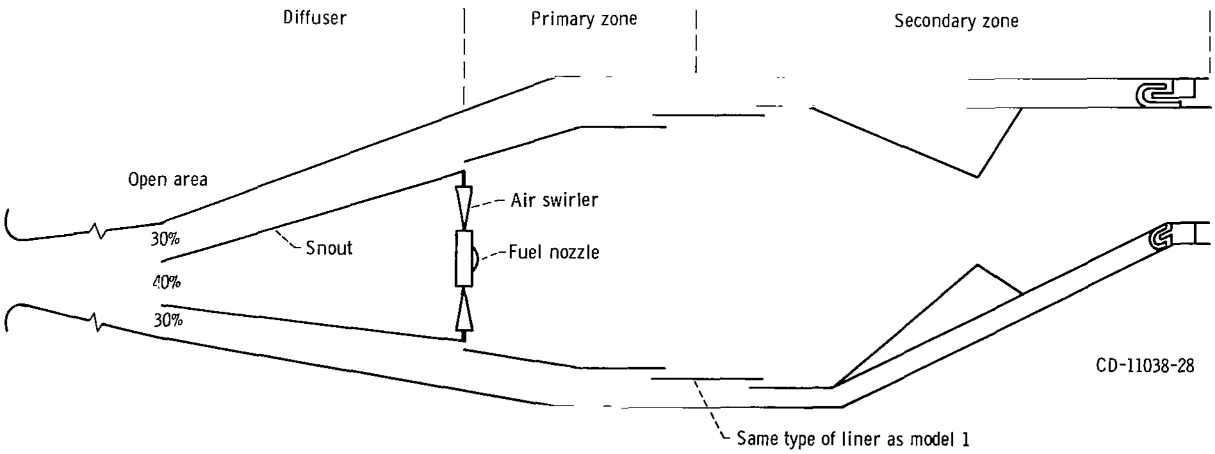
The test combustor also shown in figure 1 was a rectangular segment which simulated an annular combustor design. A jet fuel conforming to ASTM A-1 specifications was used in all of the tests. The fuel had an average hydrogen to carbon ratio of 0.161 and a lower heating value of 43 000 joules per gram (18 600 Btu/lb). Ignition was obtained with a capacitor ignitor with a maximum energy of 20 joules.

Combustor models. - The three combustor models used in this investigation are shown in figure 2. Each combustor was 0.610 meter (24 in.) long, which included a diffuser length of 0.292 meter (11.5 in.) and a combustor burning length of 0.317 meter (12.5 in.). The combustors had a cross section of 0.053 by 0.305 meter (2.1 by 12 in.) at the diffuser inlet, 0.051 by 0.305 meter (2 by 12 in.) at the combustor exit, and a maximum cross section of 0.153 by 0.305 meter (6 by 12 in.).

Combustor model 1, (fig. 2(a)) had an inlet snout open-area that was 20 percent of the combustor inlet area. The main portion of the airflow that was captured by the snout passed through the air swirlers, and a small portion, approximately 6 percent of the total diffuser airflow, passed through the cooling slots in the face plate shown in figure 3(a). This airflow provided film cooling of the side plates. The remaining airflow that bypassed the snout was admitted into the primary mixing zone through contin-

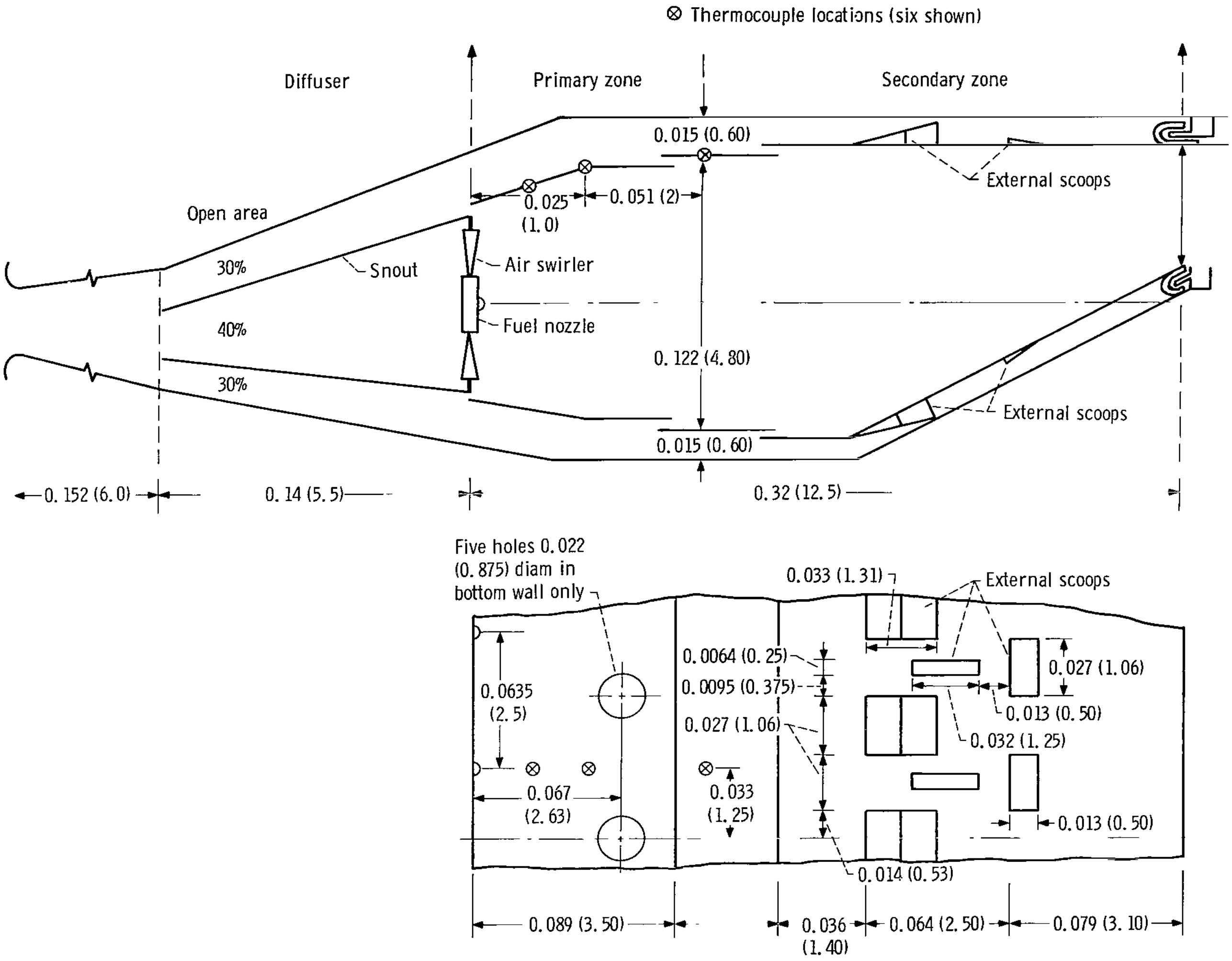


(a) Model 1.



(b) Model 2 (same dimensions as Model 1 except for the snout).

Figure 2. - Test combustors. (Dimensions are in meters (inches)).



(c) Model 3.

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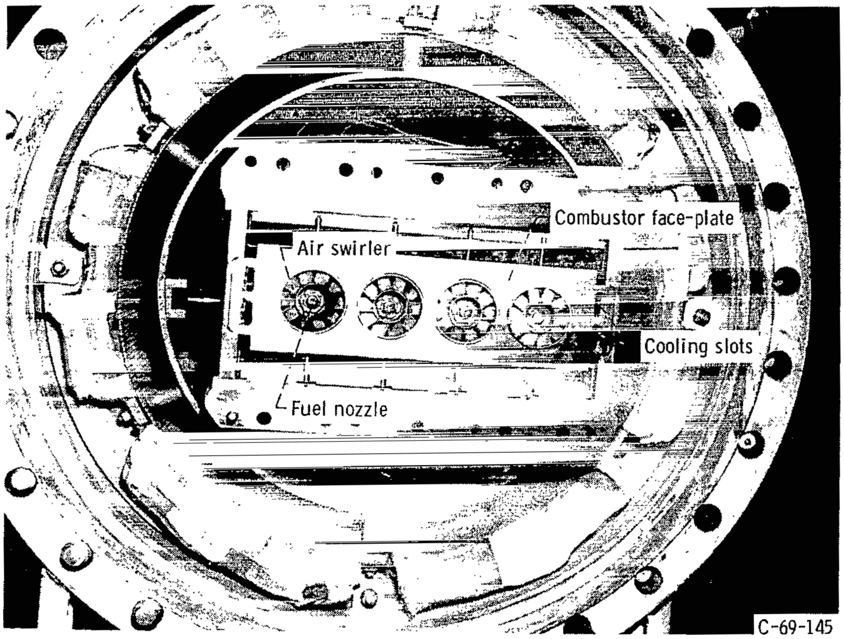
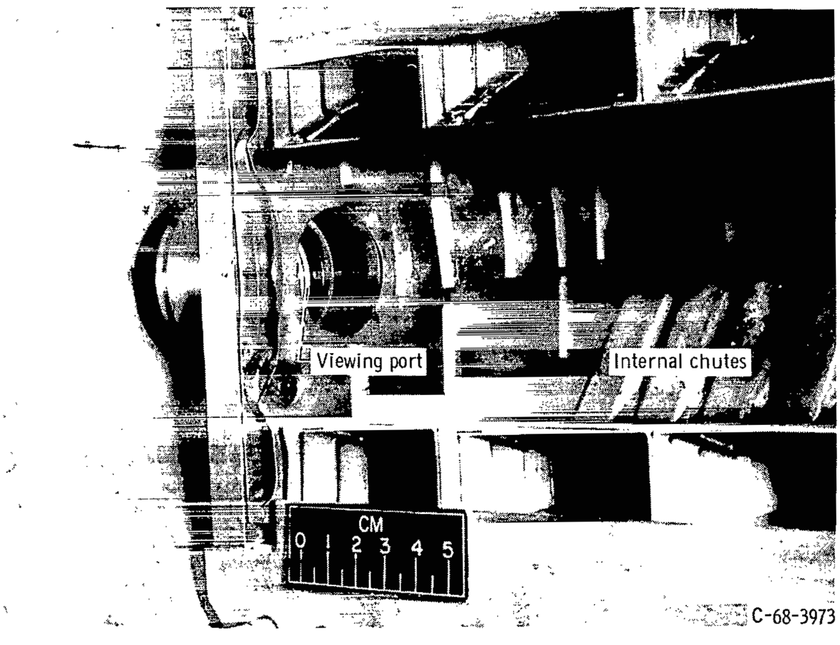
Figure 2. - Concluded.

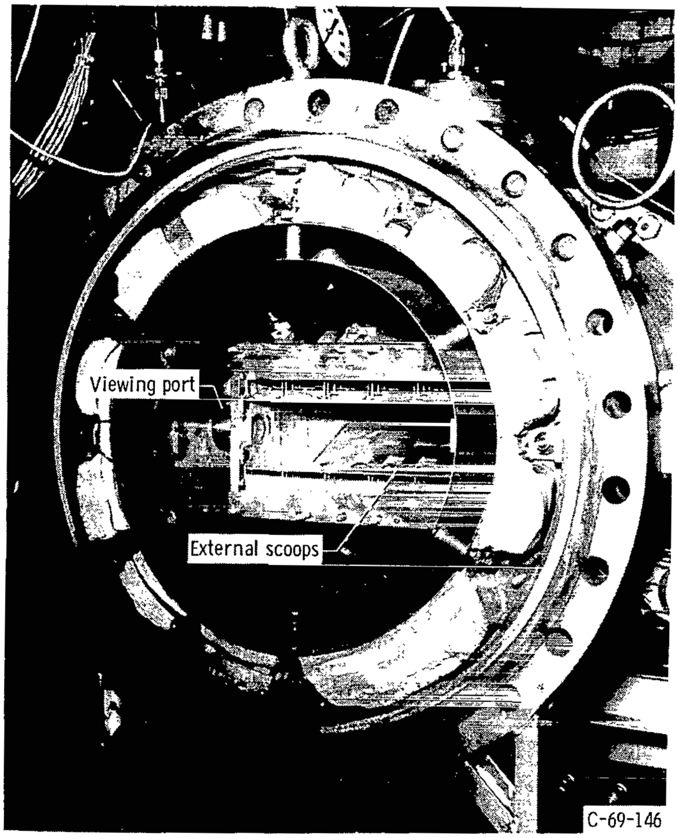


(a) Combustor model 1 primary zone inlet (looking upstream).



(b) Combustor model 2 secondary zone (looking downstream).

Figure 3. - Photographic views of combustor components.



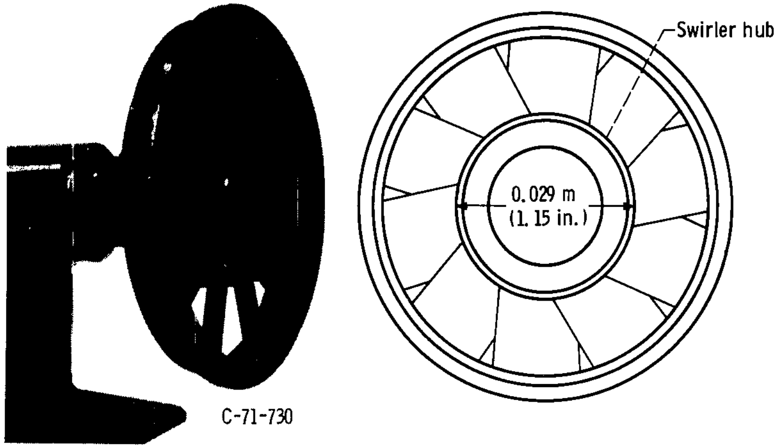
(c) Combustor model 3 secondary zone (looking downstream).
Figure 3. - Concluded.

uous liner film-cooling slots and into the secondary mixing zone by means of internal chutes.

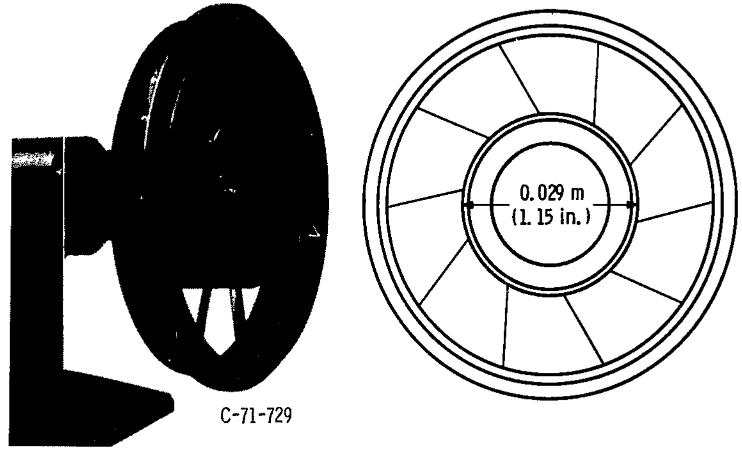
Combustor model 2 (fig. 2(b)) was similar to combustor model 1 and differed only in that the inlet snout open-area was 40 percent of the total combustor inlet area. A photograph of the internal chutes used in the combustor models 1 and 2 are shown in figure 3(b).

Combustor model 3 (fig. 2(c)) was similar to combustor model 2 except that there were five 0.022-meter (0.875-in.) holes in the bottom of the primary zone wall. Also, the secondary zone used external scoops instead of internal chutes. A photograph of the external scoops used for combustor model 3 is shown in figure 3(c).

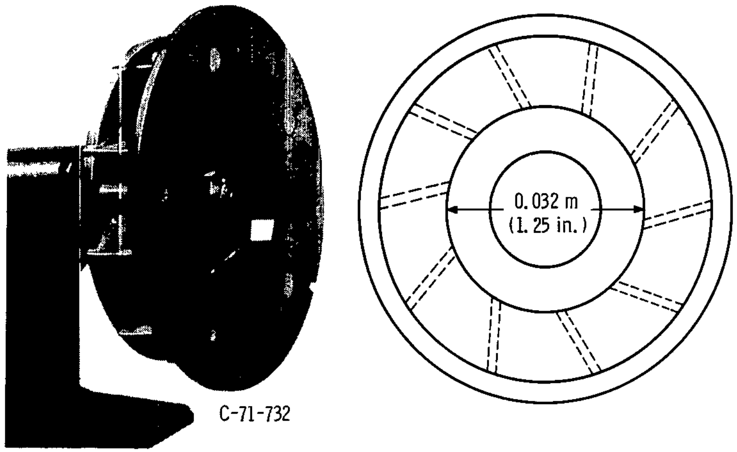
The dilution-air entry designs used for secondary-zone mixing were based on information obtained from reference 5 in which 13 different dilution-air entry methods were investigated for short-length combustors. The internal chutes shown in figure 2(a) were mounted in relatively narrow and closely spaced rectangular holes as recommended in reference 5. The external scoop design (fig. 2(c)) which was used for combustor



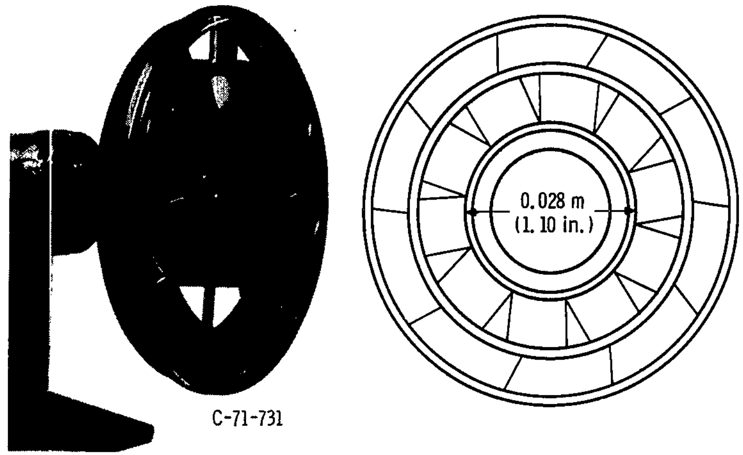
(a) Type 1, 55° axial swirler; open area, 0.00151 square meter (2.346 in.²).



(b) Type 2, 70° axial swirler; open area, 0.00151 square meter (2.346 in.²).



(c) Type 3, 70° tangential swirler; open area 0.00079 square meter (1.227 in.²).



(d) Type 4, dual-concentric swirler; open area, 0.00167 square meter (2.588 in.²).

Figure 4. - Primary inlet air swirlers; outside diameters, 0.056 meter (2.19 in.).

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model 3 was also developed in reference 5 where results showed that mixing was improved for flush holes of rectangular shape by enlarging the holes and increasing the hole spacing.

Air swirlers. - The four types of air swirlers tested are shown in figure 4. The open area of each swirler was calculated as the difference between the frontal area (based on the outside diameter) and the area of the hub of the swirler. In most of the combustion tests, the swirlers were installed so that each one rotated the air in the same direction. The two axial swirlers, types 1 and 2, produced 55° and 70° hollow cone swirls, respectively, around the fuel spray. The type 3 swirler produced a 70° tangential swirl and had approximately one-half the open area of the axial swirlers. The type 4 dual-concentric swirler produced an inner cone swirl of 50° and an outer cone swirl of 70° rotating in opposite directions.

Fuel nozzles. - A simplex type of fixed area fuel nozzle, having a spray angle of approximately 90°, was used in most of the combustor tests. For the blowout tests, a similar fuel nozzle was used which produced a higher pressure drop. For comparison of smoke numbers, additional tests were made with variable area fuel nozzles at pressure drops of 14 and 27 atmospheres (200 and 400 psi), respectively. Variations in flow rates with pressure drops are given for all types of fuel nozzles in table I.

TABLE I. - FUEL NOZZLE FLOW RATE VARIATION

WITH PRESSURE DROP

Type of fuel nozzle	Pressure drop, atm	Flow rate		Pressure drop, atm	Flow rate	
		kg hr	lb hr		kg hr	lb hr
	Used in most tests			Used in blow-out tests		
Fixed area	20	204	450	20	91	200
	1.7	54.5	120	1.7	23	50
	Low pressure type			High pressure type		
Variable area	20	375	825	27	261	575
	15	261	575	20	182	400

Instrumentation stations. - Combustor instrumentation stations are shown schematically in figure 5. The inlet air temperatures were measured with eight Chromel-Alumel thermocouples mounted in the inlet duct at section A-A as shown in figure 5. Inlet total pressures were measured at the same station by four stationary rakes consisting of three total-pressure tubes each. The total-pressure tubes were connected to differential-

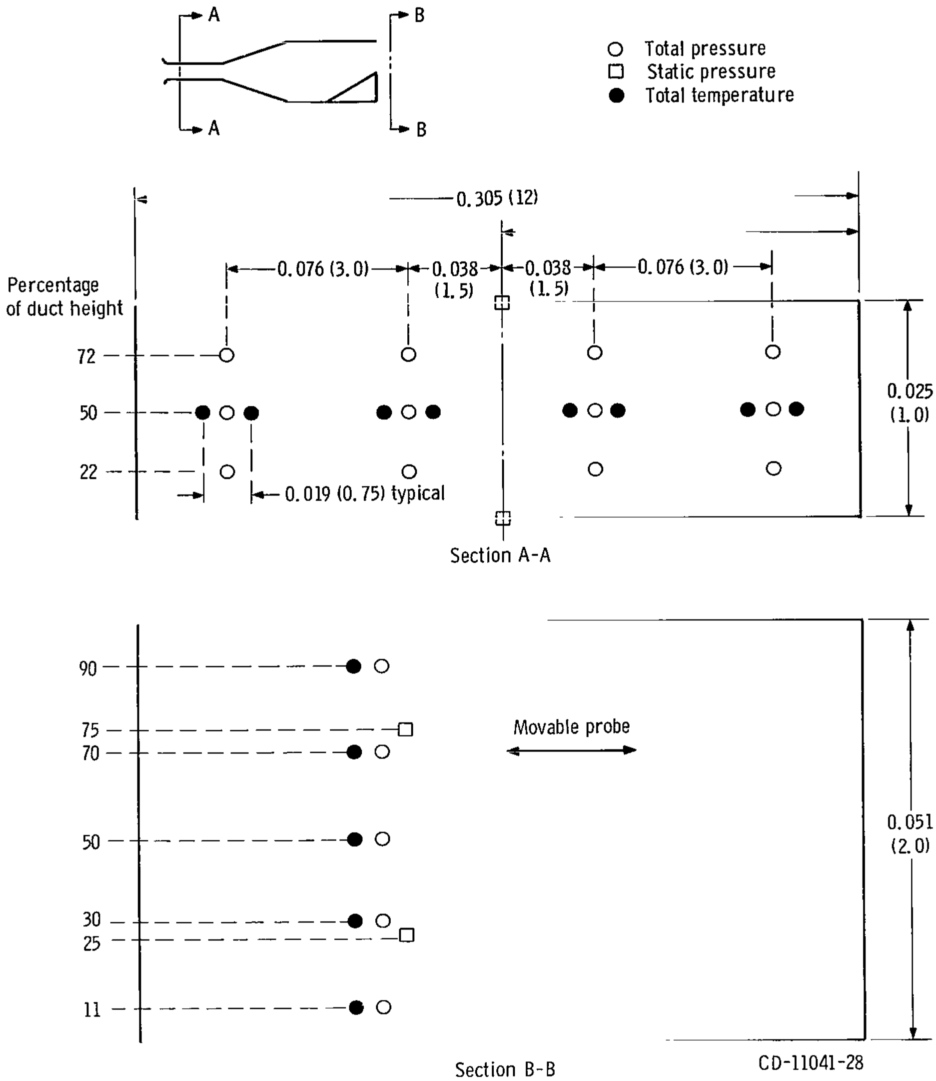


Figure 5. - Instrumentation details and locations. (Dimensions are in meters (in.)).

pressure strain-gage transducers that were balanced by wall static-pressure taps located at the top and bottom of the duct.

Combustor outlet temperature and pressure were measured with a traversing exhaust probe mounted at section B-B shown in figure 5. The probe consisted of 12 elements; five aspirating platinum/platinum 13-percent rhodium total temperature thermocouples, five total pressure tubes, and two wedge-shaped static pressure tubes. The pressure tubes were connected to strain-gage transducers. A photograph of the exhaust probe is shown in figure 6. Automatic adjustable counters, one for travel and one for dwell time, were used in traversing the combustor cross-section. Combustor outlet

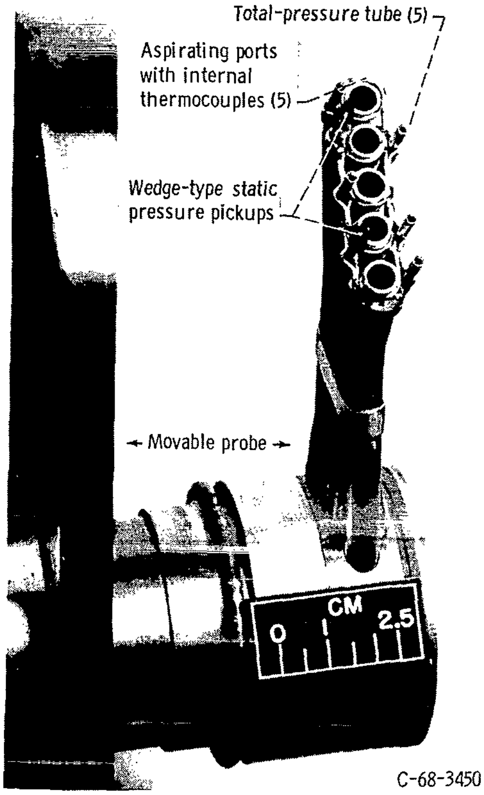


Figure 6. - Exhaust rake at section B-B (see fig. 5).

temperatures and pressures were taken for every 1.27 centimeter of travel for 23 locations across the combustor exhaust.

Combustion air and gaseous fuel flows were measured by sharp edged orifices, installed according to ASME specifications. ASTM A-1 fuel flows were measured with two turbine flowmeters connected in series. Redundancy in measurement permitted a crosscheck of flowmeter accuracy. Three sets of flowmeters were required to cover the fuel flow range.

All data were recorded on a punch paper tape (Vidar system) located remotely and printed out on a teletypewriter in the control room. The data were processed by the Lewis Central Automatic Data Processing System (ref. 6).

Flame radiance. - Total flame radiance in the primary zone was determined with an infrared radiometer at the station shown in figure 1. A description of the instrument and methods of calculation are given in reference 2.

Smoke measurement. - Exhaust smoke numbers were determined with a Von Brand smoke meter by withdrawing gas samples through the moveable exhaust probe which traversed the combustor exit at section B-B (fig. 6). The gas samples passed through a surge chamber, a moisture trap, a Whatman No. 4 filter tape, which collected the smoke

particles, a rotameter to measure sample flow rates controlled by valves upstream and downstream of the surge chamber, and a vacuum pump. The following conditions were maintained during smoke sampling tests. The gas flow rate at standard conditions was 2.83×10^{-4} cubic meter per second (0.6 ft^3/min), the pressure drop across the filter tape was approximately 1.7 newtons per square centimeter (5 in. of mercury), and the tape speed was 0.17 centimeter per second (4 in./min) which gave a sample flow rate of 2.19×10^{-5} cubic meter per second per square centimeter (0.3 $ft^3/(min)(in.^2)$) through the filter tape.

Exhaust-emission measurements. - Exhaust-emission samples were also withdrawn through the moveable exhaust probe at section B-B shown in figure 5. Total hydrocarbon and carbon monoxide concentrations were measured by flame ionization and chromatography methods, respectively. The concentration of nitrogen oxides was determined by means of the Saltzman method which was sensitive to concentrations as low as 1 part per million.

Calculations

Combustion efficiency. - The combustion efficiency was defined as the ratio of actual temperature rise to theoretical temperature rise. Combustor exit temperatures were mass weighted. The average exit temperature used for efficiency calculations was based on the total number of readings taken at the combustor exit plane. Oxygen depletion resulting from vitiation of the combustion air was taken into account in combustion efficiency calculations.

Reference velocity and Mach number. - Combustor reference velocity was computed from the measured total airflow, the maximum cross-sectional area of the combustor (0.047 m^2 (72 $in.^2$)) and the air density based on the total pressure and temperature at the diffuser inlet. The diffuser inlet Mach number was determined from the measured total airflow, and the static pressure at the diffuser inlet.

Total pressure loss. - Combustor total pressure loss $\Delta P/P$ includes the diffuser pressure loss and is defined by the following expression:

$$\frac{\Delta P}{P} = \frac{(\text{Average diffuser inlet total pressure}) - (\text{Average combustor exit total pressure})}{\text{Average diffuser inlet total pressure}}$$

Pattern factor. - The pattern factor $\bar{\delta}$ is defined by the expression

$$\bar{\delta} = \frac{T_{max} - T_{av}}{\Delta T}$$

where T_{max} is the highest local combustor exit temperature, T_{av} is the average combustor exit temperature, and ΔT is the average combustor temperature rise.

For calculations of temperature distribution parameters, non-mass-weighted temperatures were used. Approximately 10 percent of the temperature readings at each combustor side wall were disregarded to eliminate the side wall effects which are always present in sector tests.

Dimensionless axial velocity ratio. - The dimensionless axial velocity ratio $\bar{u}$ produced by the air swirlers was defined as the ratio of u (the axial component of the velocity vector at the radial coordinate, r) to u_o (the axial component of the velocity vector at the centerline). Values of $\bar{u}$ were calculated from the following expression (ref. 7):

$$\bar{u} = \frac{u}{u_o} = \left[1 - G^2\left(\frac{r}{R}\right)^2\right]^{1/2}$$

where G is the degree of swirl which is a function of the blade angle of the swirler and calculated as the ratio of the maximum tangential component of the velocity vector to u_o, r is the radius of the swirler hub (fig. 4), and R is the radius of the swirl measured from the center of the swirler to the liner wall (5.42 cm (2.13 in.)).

Smoke number. - Smoke traces on the filter tape were analyzed with a reflective densitometer which was calibrated with a Welsh Gray Scale. The smoke number, as defined in reference 8, was determined from the following expression:

$$\text{Smoke number} = 100(1 - r')$$

where r' is the ratio of the percent absolute reflectivity of the smoke trace to that of the clean filter tape.

Liner temperature. - Nine Chromel-Alumel thermocouples were installed in the liner walls of combustor model 3. The 0.15-centimeter (0.06-in.) diameter thermocouple sheaths were located in grooves milled into the liner wall, and the thermocouple junction was filled with high temperature braze. Figure 2(c) shows the location of six of the thermocouples: three in the top liner and three in the bottom liner. The remaining three thermocouples were installed in the top liner at the same distances downstream from the fuel nozzles, but displaced 0.095 meter (3.75 in.) to the left of the combustor centerline looking downstream. The three thermocouples located 0.051 meter (2 in.) downstream of the fuel nozzles gave higher readings than the other six thermocouples, and were arithmatically averaged to obtain the average liner temperature at that station. The liner temperature was also calculated by means of a heat balance as described in the appendix.

RESULTS AND DISCUSSION

The three combustor models with four types of air swirlers were tested under high-pressure inlet-air conditions by burning ASTM A-1 fuel over a range of fuel-air ratios. The test conditions are given in table II, and the experimental data are recorded in table III. Combustor performance was evaluated by comparing the combustion efficiency, total pressure loss, exit temperature profile, pattern factor, and exhaust smoke number. Also, blowout conditions and combustor liner temperature were investigated. Initially, only 55^{o} axial (type 1) swirlers were used with the combustors. The effect of swirler geometry on combustor performance is discussed later in a separate section.

TABLE II. - COMBUSTOR TEST CONDITIONS

Inlet pressure, atm	Inlet temperature		Reference velocity	
	K	^{o}R	m/sec	ft/sec
10	589	1060	21.3	70
10	756	1360	27.4	90
20	589	1060	21.3	70
20	756	1360	27.4	90
26.7	589	1060	21.3	70

Combustion Efficiency

As shown in figure 7 there was no appreciable effect of inlet-air total pressure on the combustion efficiency of the three combustor models using 55^{o} axial (type 1) swirlers. Of the three combustors, combustor model 1 which had a snout open-area of 20 percent gave the lowest combustion efficiency, particularly at high fuel-air ratios. Combustion efficiencies were fairly constant at nearly 100 percent for the combustor models 2 and 3 which had snout open-areas of 40 percent. Thus, combustion efficiency was improved by increasing the open-area of the snout from 20 to 40 percent.

TABLE III - COMBUSTOR PERFORMANCE DATA

Run	Combustor model	Swirler type	Fuel nozzles: Fixed area	Fuel nozzles: Variable area	Inlet-air pressure, atm	Inlet-air temperature, K	Inlet-air temperature, ^oR	Air flow, kg sec	Air flow, lb sec	Nominal reference velocity, m sec	Nominal reference velocity, ft sec	Fuel-area ratio	Average combustor temperature rise, K	Average combustor temperature rise, ^oF	Combustion efficiency, percent	Mach number	Combustor pressure loss, ΔP P, percent	Pattern factor	Smoke number
1	1	1	√		10	589	1060	6.17	13.6	22.1	72.5	0.0063	202	364	94.5	-----	2.96	1.09	----
2								6.13	13.5	20.6	67.7	.0065	222	399	96.3	-----	2.92	1.72	----
3								6.36	14.0	22.2	72.7	.0093	276	496	91.7	-----	3.06	1.69	----
4								6.40	14.1	22.3	73.0	.0120	339	610	89.4	-----	4.01	1.84	----
5								6.36	14.0	22.3	73.0	.0150	428	770	89.2	-----	3.70	2.00	---
6					20	584	1060	12.35	27.2	20.7	67.9	.0054	175	315	95.1	-----	2.74	1.49	----
7								12.21	26.9	20.4	67.0	.0070	219	394	93.7	-----	3.18	1.68	9.3
8								12.12	26.7	20.6	67.4	.0101	315	567	92.7	-----	2.82	1.68	23.3
9								12.17	26.8	20.5	67.3	.0125	374	674	90.8	-----	2.99	1.29	26.7
10								12.12	26.7	20.4	67.0	.0158	434	782	87.2	-----	4.56	1.84	----
11	2	1	√		10	589	1060	6.04	13.3	18.9	62.0	0.0102	369	665	97.9	-----	2.25	1.37	----
12								6.08	13.4	21.4	70.0	.0101	340	612	95.8	-----	4.15	1.04	3.3
13								6.04	13.3	21.7	71.0	.0121	471	848	98.6	-----	4.23	1.19	7
14					20			11.80	26.0	20.3	66.4	.0052	188	338	97.8	-----	3.20	1.01	1.3
15								11.99	26.4	20.6	67.4	.0072	259	467	98.0	-----	3.22	1.00	7
16								11.89	26.2	20.3	66.7	.0100	368	663	98.6	-----	3.79	1.14	7
17								12.08	26.6	20.6	67.7	.0138	473	851	99.6	-----	3.96	1.17	7
18	3	1	√		10	589	1060	6.40	14.1	22.0	72.0	0.0081	308	554	99.6	-----	----	----	----
19								6.45	14.2	22.2	72.9	.0098	360	648	98.9	-----	----	----	---
20								6.49	14.3	22.4	73.4	.0124	451	811	98.8	-----	----	---	----
21								6.45	14.2	22.2	72.8	.0181	612	1102	96.7	-----	----	----	----
22						756	1360	6.08	13.4	26.7	87.6	.0102	352	633	98.6	-----	----	----	---
23						756	1360	6.04	13.3	26.8	87.9	.0132	444	800	98.0	-----	----	----	----
24						756	1360	6.08	13.4	26.7	87.7	.0161	546	983	98.5	-----	----	----	----
25					20	589	1060	12.30	27.1	21.0	68.7	.0069	264	475	99.4	-----	----	----	----
26								12.30	27.1	21.0	68.6	.0099	372	669	99.6	-----	----	----	----
27								11.99	26.4	20.6	67.7	.0131	464	836	97.7	-----	----	----	----
28								12.12	26.7	20.8	68.1	.0129	473	852	99.1	-----	----		
29								12.30	27.1	21.1	69.2	.0158	580	1045	100.1	-----	----	----	----
30								12.35	27.2	21.0	69.0	.0189	668	1203	99.0	-----	----	----	----
31						756	1360	12.30	27.1	26.8	87.9	.0069	246	143	99.1	-----	----	----	----
32								12.58	27.7	27.3	89.4	.0067	241	433	99.1	-----	----	---	----
33								12.21	26.9	26.5	86.8	.0100	362	652	99.8	-----	----	----	--
34								12.12	26.7	26.3	86.1	.0131	457	822	99.0	-----	----	----	--
35								12.17	26.8	26.4	86.4	.0130	454	818	99.0	-----	----	----	-
36								12.30	27.1	26.4	86.5	.0159	534	962	98.0	-----	----	---	-
37								12.30	27.1	27.1	88.7	-----	---	---	----	0.342	5.67	----	--
38					10	589	1060	5.99	13.2	21.4	70.3	-----	---	---	----	.282	4.26	----	-
39	1	1			10	567	1021	6.36	14.0	21.3	69.8	-----	---	---	-----	0.282	2.73	----	--
40					10	575	1035	8.04	17.7	27.4	89.9	-----	---	---	-----	.373	5.31	----	-
41					10	569	1024	9.67	21.3	32.8	107.5	-----	---	---	-----	.470	7.60	----	--
42					20	564	1015	12.49	27.5	20.9	68.6	-----	---	---	-----	.278	2.96	----	----
43					26.7	574	1033	11.53	25.4	14.8	48.6	-----	---	---	-----	.221	2.57	----	--
44	3	2			10	589	1060	6.49	14.3	22.3	73.0	0.0088	356	641	102.1	-----	5.96	0.52	10.6
45					10			6.45	14.2	22.4	73.5	.0116	447	805	101.0	-----	5.65	.80	31.1
46					10			6.49	14.3	22.6	74.1	.0143	527	949	100.0	----	5.86	.96	29.8
47					20			11.80	26.0	20.6	67.6	.0069	279	503	101.7	-----	4.69	.46	29.5
48					20			11.94	26.3	20.9	68.5	.0097	376	677	100.8	----	4.42	.84	
49					20			11.94	26.3	21.0	68.9	.0127	480	864	100.6	-----	3.55	.81	34.4
50	3	3			10	589	1060	6.49	14.3	22.3	73.2	0.0097	382	687	101.3	-----	---	1.48	4.6
51					20			11.08	24.4	19.4	63.5	.0059	228	410	99.8	----	---	1.59	0
52								11.26	24.8	19.8	64.8	.0078	305	549	100.8	----	-	1.48	1.3
53								12.03	26.5	20.7	67.9	.0073	289	520	100.7	-----	---	1.46	2.0
54						756	1360	12.67	27.9	27.1	88.9	.0054	214	385	100.6	-----	---	1.53	4.1
55					10	756	1360	6.45	14.2	28.8	94.5	.0097	269	484	98.5	-----	---	1.61	0

TABLE III. - Concluded. COMBUSTOR PERFORMANCE DATA

Run	Combustor model	Swirler type	Fuel nozzles: Fixed area	Fuel nozzles: Variable area	Inlet-air pressure, atm	Inlet-air temperature: K	Inlet-air temperature: °R	Air flow: kg/sec	Air flow: lb/sec	Nominal reference velocity: m/sec	Nominal reference velocity: ft/sec	Fuel-air ratio	Average combustor temperature rise: K	Average combustor temperature rise: °F	Combustion efficiency, percent	Mach number	Combustor pressure loss, ΔP/P, percent	Pattern factor	Smoke number
56	3	4	√		10	589	1060	6.40	14.1	22.0	72.0	0.0098	362	652	98.9	-----	----	0.68	0
57								6.40	14.1	22.2	72.9	.0126	456	821	98.7	-----	----	.64	.7
58								6.36	14.0	22.1	72.4	.0156	552	994	98.3	-----	----	.65	.0
59								6.45	14.2	22.4	73.4	.0181	622	1120	97.5	-----	----	.67	0.0
60					20			11.49	25.3	18.9	61.9	.0075	290	522	99.7	-----	----	.71	2.7
61					20			11.40	25.1	18.5	60.7	.0107	402	724	99.3	-----	----	.66	3.3
62					20			11.40	25.1	18.6	61.0	.0141	507	912	98.3	-----	----	.75	.0
63	3	1		[c]400	20	589	1060	12.03	26.5	20.7	68.0	0.0071	283	510	103.0	-----	----	0.44	63.2
64								12.03	26.5	20.7	68.0	.0102	398	716	100.7	-----	----	1.48	54.0
65								12.62	27.8	20.9	68.4	.0133	522	939	103.8	-----	----	.57	62.0
66								11.85	26.1	20.7	68.0	.0152	625	1126	-----	-----	----	.74	74.0
67				[c]200				12.49	27.5	21.6	70.9	.0069	268	482	100.8	0.287	4.41	.39	42.0
68								12.26	27.0	20.9	68.5	.0101	384	691	100.7	.275	4.39	.43	39.0
69								12.17	26.8	20.9	68.6	.0130	581	1046	-----	.275	4.33	.74	32.0
70								12.21	26.9	21.0	68.9	.0160	---	----	-----	-----	----	----	27.0
71	3	1			26.7	589	1060	12.94	28.5	17.0	55.7	0.0063	259	467	106.2	0.222	----	0.33	38.2
72								12.12	26.7	16.3	53.3	.0106	409	736	101.9	.210	----	.58	27.9
73								11.89	26.2	16.0	52.3	.0139	523	941	101.3	.205	----	.60	24.6
74								12.03	26.5	16.3	53.2	.0170	653	1176	105.3	.209	----	.60	17.8
75	3	1	√		20			12.08	26.6	21.2	69.4	.0071	289	520	[a]105.4	.276	----	.30	18.4
76								12.03	26.5	21.2	69.4	.0102	408	734	[a]106.1	.276	----	.40	11.8
77								12.08	26.6	21.3	69.9	.0132	523	942	[a]106.8	.278	----	.38	9.9
78								12.03	26.5	21.3	69.8	.0163	631	1136	[a]105.9	.277	----	.46	2.0
79								12.03	26.5	21.1	69.2	.0194	736	1325	[a]105.5	.276	----	.50	1.3
80								12.12	26.7	21.3	69.8	.0220	827	1488	[a]106.2	.278	----	.52	0
81					10	589	1060	6.17	13.6	22.0	72.1	0.0101	413	743	[a]108.5	0.286	----	0.36	17.1
82								6.27	13.8	21.0	69.0	.0129	521	937	[a]108.0	.280	----	.38	9.2
83								6.13	13.5	21.4	70.3	.0160	621	1118	[a]106.3	.282	----	.38	1.3
84								6.13	13.5	21.1	69.2	.0187	715	1288	[a]105.5	.280	----	.44	1.3
85						487	875	6.13	13.5	18.2	59.6	.0101	423	761	[a]108.0	.256	----	.48	30.3
86								6.22	13.7	18.4	60.2	.0127	524	943	[a]107.8	.260	----	.44	15.8
87								6.22	13.7	18.3	60.0	.0157	636	1145	[a]107.8	.260	----	.44	6.6
88								6.22	13.7	18.3	60.1	.0186	742	1335	[a]107.9	.261	----	.44	.0
89						756	1360	6.13	13.5	28.2	92.5	.0099	388	699	[a]109.0	.308	----	.34	3.9
90								6.13	13.5	28.2	92.4	.0129	493	887	[a]107.9	.327	----	.32	1.3
91								6.17	13.6	28.0	91.8	.0158	594	1070	[a]107.2	.326	----	.36	1.3
92								6.13	13.5	27.8	91.3	.0190	693	1247	[a]105.7	.326	----	.39	1.3
93					20	589	1060	11.89	26.2	21.2	69.5	.0204	754	1357	[a]103.5	.276	----	.61	6.0
94	3	1	√			756	1360	11.44	25.2	24.6	80.8	.0075	271	488	[a]97.2	.290	----	.23	--
95								12.03	26.5	26.3	86.1	.0072	269	484	[a]101.9	.309	----	.23	---
96								11.99	26.4	26.1	85.5	.0103	387	696	[a]103.6	.307	----	.27	
97								11.94	26.3	26.2	85.8	.0134	488	879	[a]102.0	.307	----	.40	---
98								11.94	26.3	26.2	85.9	.0166	597	1075	[a]102.6	.307	----	.52	---
99	2	2	√			589	1060	6.27	13.8	22.4	73.3	.0098	347	625	[b]97.5	----	----	1.13	4.0
100		2						6.27	13.8	22.4	73.2	.0126	436	784	[b]96.8	----	----	1.06	7.3
101		3						6.17	13.6	21.9	71.7	.0101	347	625	[b]96.5	----	----	1.17	33.8
102		3						6.27	13.8	22.2	72.9	.0129	434	782	[b]96.0	----	----	1.31	53.6
103		4						7.08	15.6	23.7	77.7	.0089	304	547	[b]96.1	----	----	1.32	1.3
104		4						7.08	15.6	23.7	77.7	.0113	382	687	[b]95.5	----	----	1.35	1.3

[a]Calculated from arithmetically averaged temperatures.
[b]Calculated from estimated mass weightings.
[c]Fuel pressure drop.

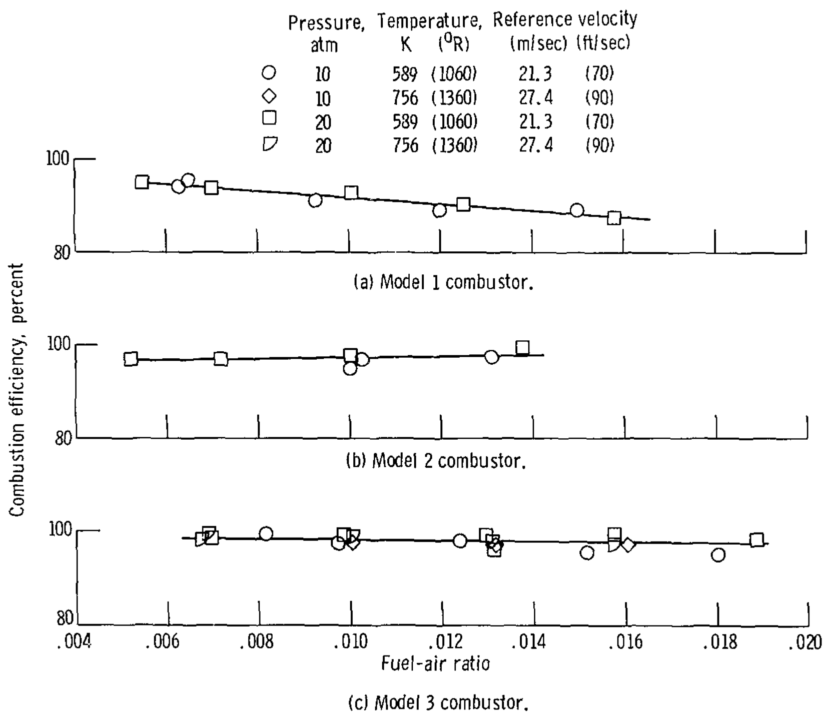


Figure 7. - Combustion efficiency with fixed area fuel nozzles and type 1 swirlers.

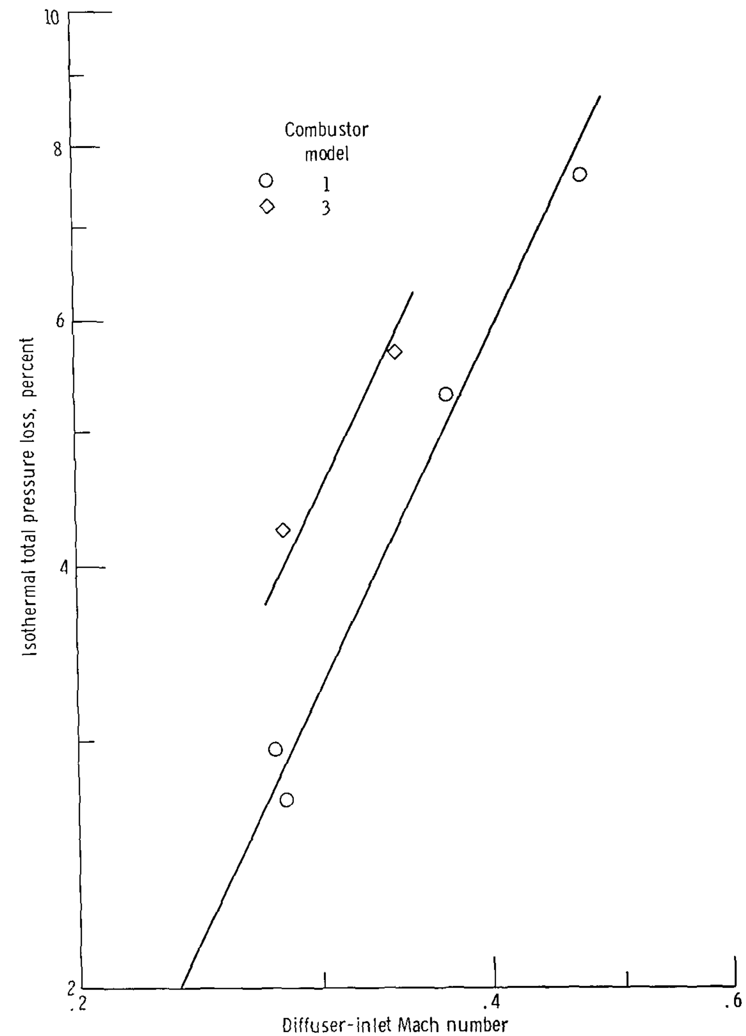


Figure 8. - Relation between isothermal total pressure loss and diffuser-inlet Mach number for Model 1 and 3 combustors with type 1 swirlers. Inlet-air pressure, 10 atmospheres inlet-air temperature, 589 K (1060° R).

Combustor Total Pressure Loss

A comparison of isothermal total pressure losses for combustors model 1 and 3 is shown in figure 8. Increasing the open-area of the combustor snout from 20 to 40 percent and changing from internal chutes to external scoops increased the isothermal total pressure loss from 3.2 for combustor model 1 to 4.3 percent for combustor model 3 at a diffuser inlet Mach number of 0.26 and from 4.4 to 5.8 percent, respectively, at a Mach number of 0.35. Thus, an increase in total-pressure loss occurred when primary-zone mixing was improved by increasing the airflow through the swirlers. Also, it should be noted that the combustor total pressure loss included that of the diffuser.

Exit Temperature Profile

A comparison of exit temperature profiles of combustor models 1 and 2 with type 1 swirlers, at a total pressure of 20 atmospheres, is shown in figure 9. The best profile

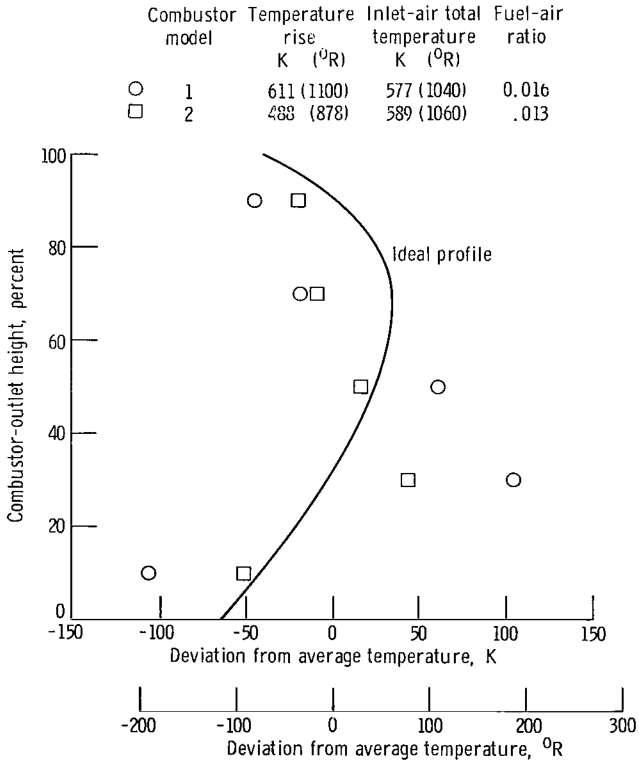


Figure 9. - Exit temperature profiles for combustor models 1 and 2 with fixed area fuel nozzles and type 1 swirlers. Reference velocity, 21.3 meters per second (10 ft/sec); inlet pressure, 20 atmospheres.

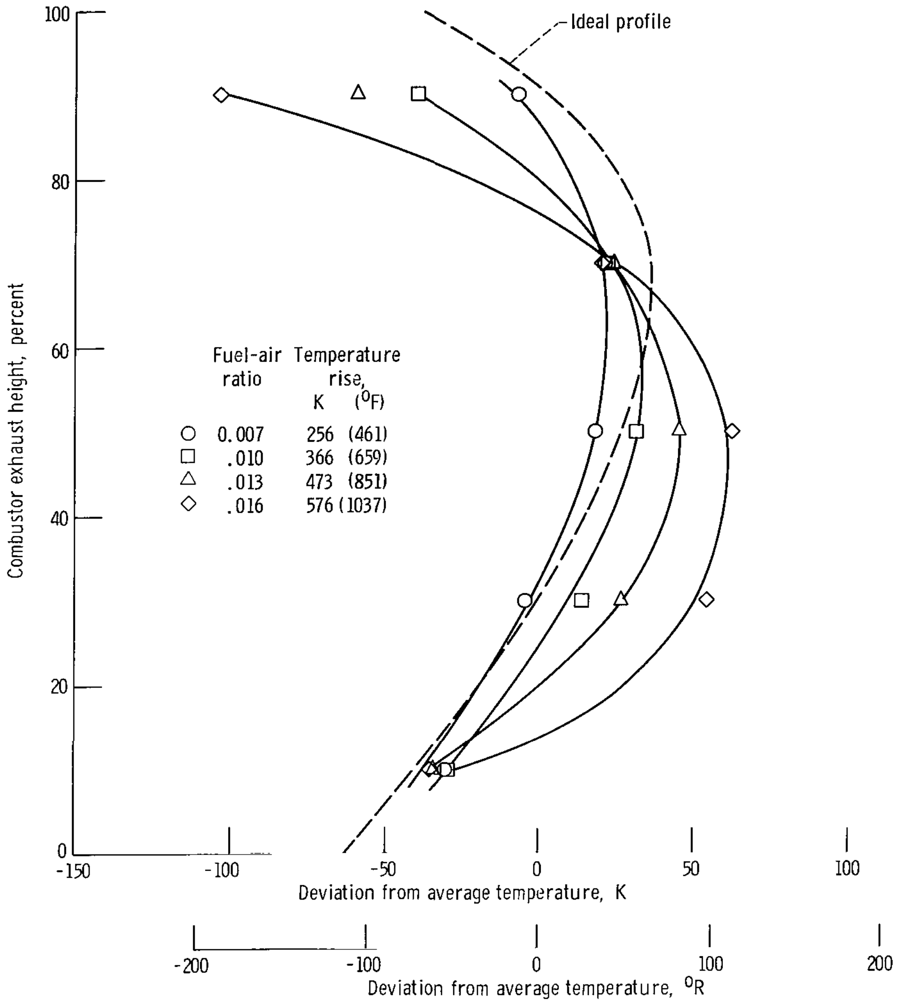


Figure 10. - Effect of fuel-air ratio on exit temperature profile. Combustor model 3; fixed area fuel nozzles; type 1 swirler; reference velocity 27.4 meters per second (90 ft/sec); inlet-air total temperature 755 K (1360° R); total pressure, 20 atmospheres.

was obtained with relatively high airflow through the swirlers, that is, with combustor model 2. Thus, increasing primary-zone mixing by increasing the airflow through the swirlers improved the exit temperature profile, but also increased the pressure loss.

The effect of fuel-air ratio on the exit temperature profile, is shown in figure 10, for the combustor model 3. Operation of the combustor at a low fuel-air ratio (0.007) gave the most nearly ideal profile. As shown in figure 11, very little effect was observed of the inlet-air total pressure on the exit temperature profile for combustor model 3 at a constant fuel-air ratio. Also, simultaneously increasing air temperature and reference velocity gave very little effect on the profile. Similar results were obtained with combustor models 1 and 2. Using alternating clockwise and counterclockwise

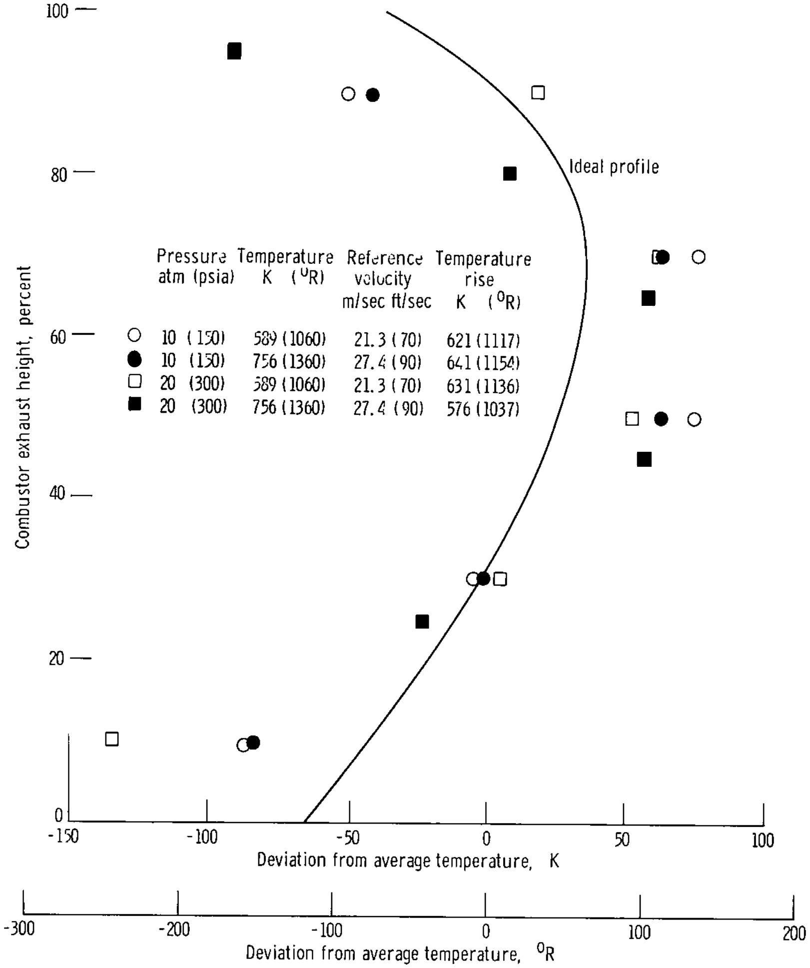


Figure 11. - Exit temperature profile for combustor model 3 with fixed area fuel nozzles, type 1 swirlers and fuel-air ratio of 0.016.

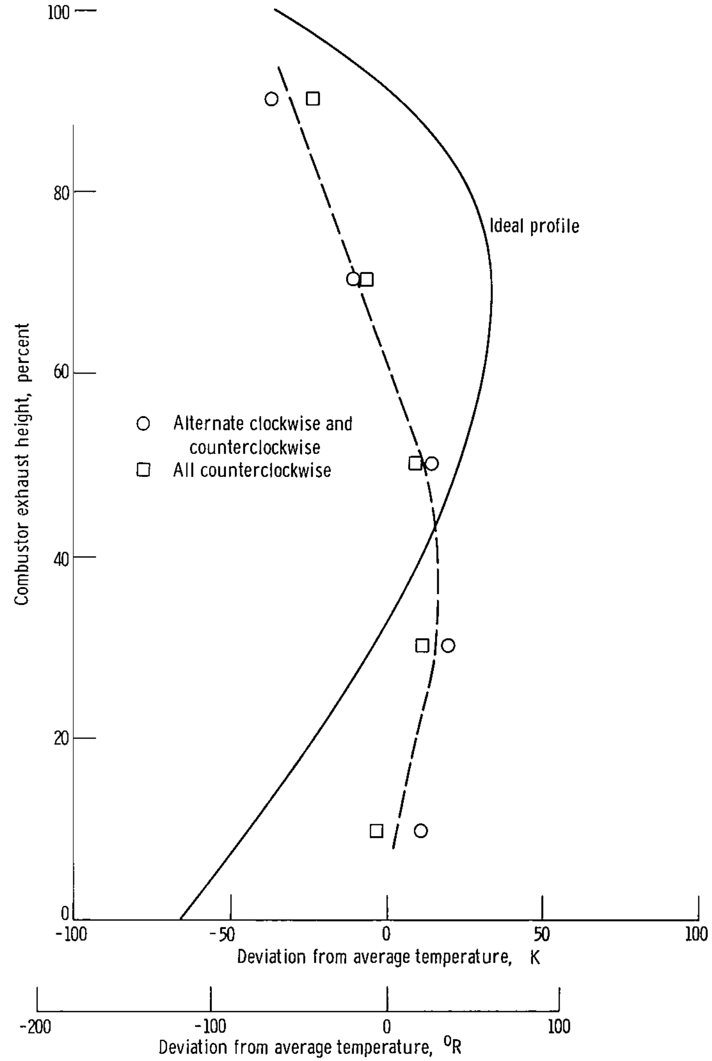


Figure 12. - Comparison of exit temperature profiles for different swirler arrangements with combustor model 3, fixed area fuel nozzles, and type 1 swirlers.

swirlers had very little effect on the exit temperature profile for combustor model 3 as shown in figure 12.

Pattern Factor

Increasing the fuel-air ratio tended to increase pattern factors for combustor model 3 especially at higher pressures, as shown in figure 13. The effect of inlet-air

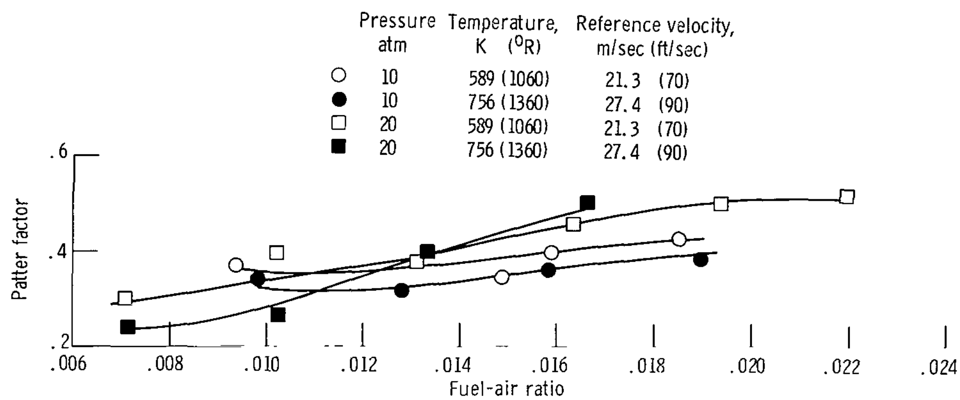


Figure 13. - Pattern factors for the combustor model 3 with fixed area fuel nozzles and type 1 swirlers.

total pressure on the pattern factor was dependent on the fuel-air ratio. At low fuel-air ratios, the pattern factor increased with decreasing pressures, but at high fuel-air ratios, the pattern factor increased with increasing pressure. This effect was not tested with the combustor models 1 and 2.

Exhaust Smoke Number

The effect of fuel-air ratio on the exhaust smoke number for the three combustors operating at an inlet-air total pressure of 20 atmospheres is shown in figure 14. With the combustor model 1 having relatively low airflow through the swirlers, smoke numbers increased at the higher fuel-air ratios. However, with relatively high airflow through the swirlers (models 2 and 3), smoke numbers decreased with increasing fuel-air ratios. The lowest smoke numbers were obtained with the combustor model 2 which used relatively high airflow through the swirlers and eight internal secondary-zone mixing chutes.

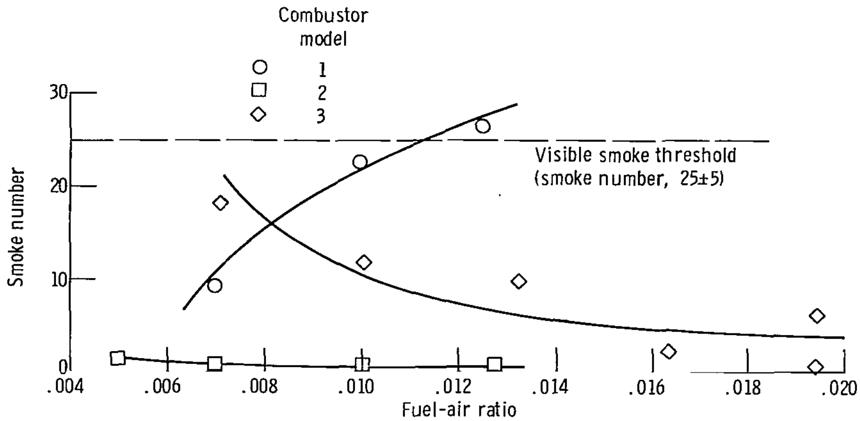


Figure 14. - Smoke number comparison of combustors with fixed area fuel nozzles and type 1 swirlers. Combustor reference velocity, 21.3 meters per second (70 ft/sec); inlet air temperature, 578 K (1060° R); and pressure of 20 atmospheres.

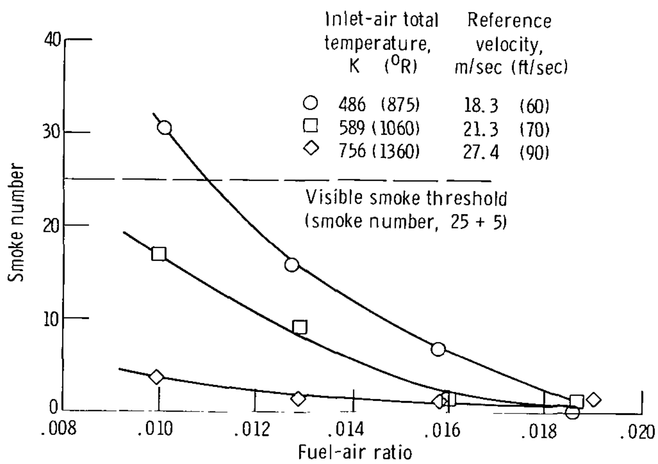


Figure 15. - Relation between smoke number and inlet-air total temperature with combustor model 3, fixed area fuel nozzles, and type 1 swirlers at pressure of 10 atmospheres.

Smoke numbers decreased when inlet-air total temperature and reference velocity were simultaneously increased. This was particularly evident at low fuel-air ratios, as shown in figure 15 for combustor model 3 for an inlet-air total pressure of 10 atmospheres. It was also found (fig. 16) that the combined effect of simultaneously increasing the inlet-air total pressure from 20 to 26.7 atmospheres while also decreasing the reference velocity from 21.3 to 16 meters per second (70 to 52.5 ft/sec) gave a considerable increase in the smoke number with combustor model 3. At an inlet-air total pressure of 26.7 atmospheres, smoke numbers were above the visible smoke threshold (25±5) at fuel-air ratios below approximately 0.015. Similar tests were not conducted

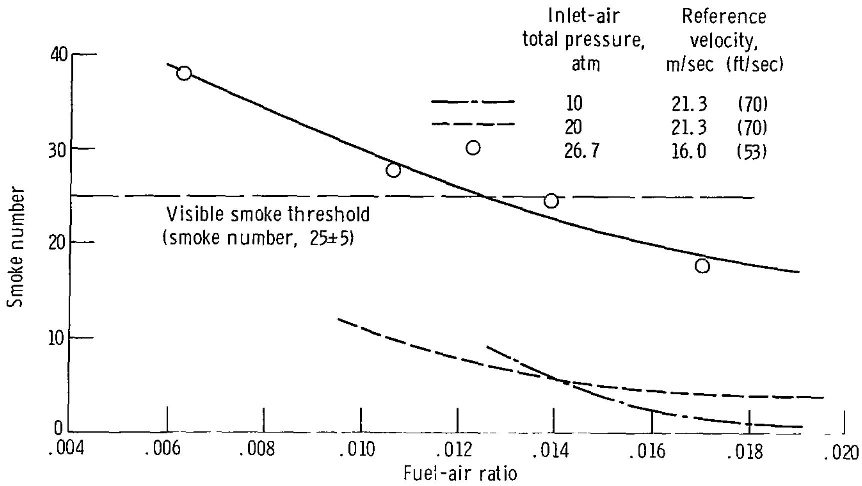


Figure 16. - Relation between smoke number and inlet-air total pressure with combustor model 3, fixed area fuel nozzles, and type 1 swirlers at inlet-air total temperature of 589 K (1060° R).

with the combustor model 1 or 2. A more extensive study of combustor smoke formation is given in reference 2.

Additional Tests for Exhaust-Emission Components

A series of tests at simulated idle, cruise, and takeoff operating conditions were made to determine the concentrations of total hydrocarbons, carbon monoxide, and nitrogen oxides in the exhaust gases. Exhaust-emission concentrations and smoke numbers that were obtained by sampling the exhaust of combustor model 3 are given in table IV. These data show that both the concentration of nitrogen oxides and the smoke number increased in going from idle to cruise and to takeoff conditions as inlet-air pressure and temperature were simultaneously increased. However, the concentrations of total hydrocarbons and carbon monoxide decreased. Similar trends are shown in table IV for a typical combustor that is described in reference 9. However, smoke number data are not presented in reference 9. Thus, the two combustors cannot be compared as to exhaust smoke formation.

Combustor Liner Temperature

As smoke formation increased, it was found that the radiant heat-transfer rate from the flame to the combustor liner increased, and liner temperature increased. This relation between smoke number and total radiance is shown in figure 17 for the combustor

TABLE IV. - EXHAUST-EMISSION COMPONENTS FOR IDLE, CRUISE, AND TAKEOFF COMBUSTOR OPERATING CONDITIONS

Simulated engine condition	Combustor operating conditions				Exhaust-emission components						
	Fuel-air ratio	Inlet-air total pressure, atm	Inlet-air total temperature		Total hydrocarbons, ppm[a]	Grams carbon per kilogram fuel	Carbon monoxide, ppm	Grams carbon monoxide per kilogram fuel	Total nitrogen oxides, ppm[b]	Grams nitric oxide per kilogram	Smoke number
			K	°R							
Combustor model 3[c]											
Idle	0.007	4	422	760	360	21.4	180	25.0	6	0.89	7
Cruise	0.015 to 0.002	10	589	1060	4 to 39	0.11 to 0.75	0 to 30	0 to 1.35	6 to 17	0.42 to 0.82	6 to 9
Takeoff	0.018	20	756	1360	9	0.21	0 to 30	0 to 1.64	8 to 46	0.47 to 2.69	8 to 12
YTF-33-P1(JT3D) combustor (ref. 9)[d]											
Idle	0.0072	--	---	----	398 to 880	23.1 to 51.0	364 to 547	49.1 to 73.8	4 to 10	0.58 to 1.45	-----
Cruise	.0126	--	---	----	3 to 7	0.10 to 0.23	1 to 13	0.08 to 1.01	91 to 109	7.57 to 9.06	-----
Takeoff	.0130	--	---	----	3 to 7	0.10 to 0.23	1 to 12	0.08 to 0.90	98 to 119	7.90 to 9.60	-----

[a]Parts per million is based on single carbon molecules.

[b]Parts per million is based on NO_2 molecules.

[c]Reference velocities ranged from 21.3 to 30.5 m sec (70 to 100 ft/sec).

[d]Estimated engine compressor ratio, 12.1.

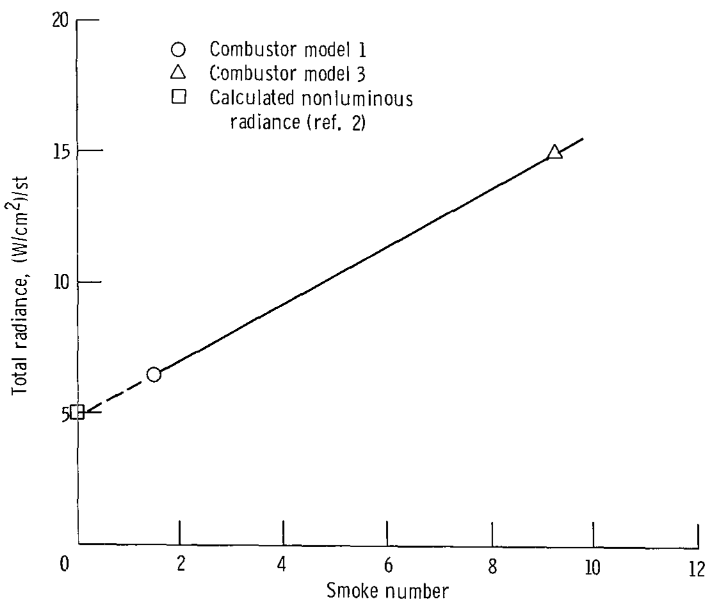


Figure 17. - Relation between smoke number and radiance with combustor models 1 and 3, fixed area fuel nozzles, and type 1 swirlers. Reference velocity, 21.3 meters per second (70 ft/sec); inlet air temperature, 589 K (1060° R); pressure, 10 atmospheres; fuel-air ratio, 0.008.

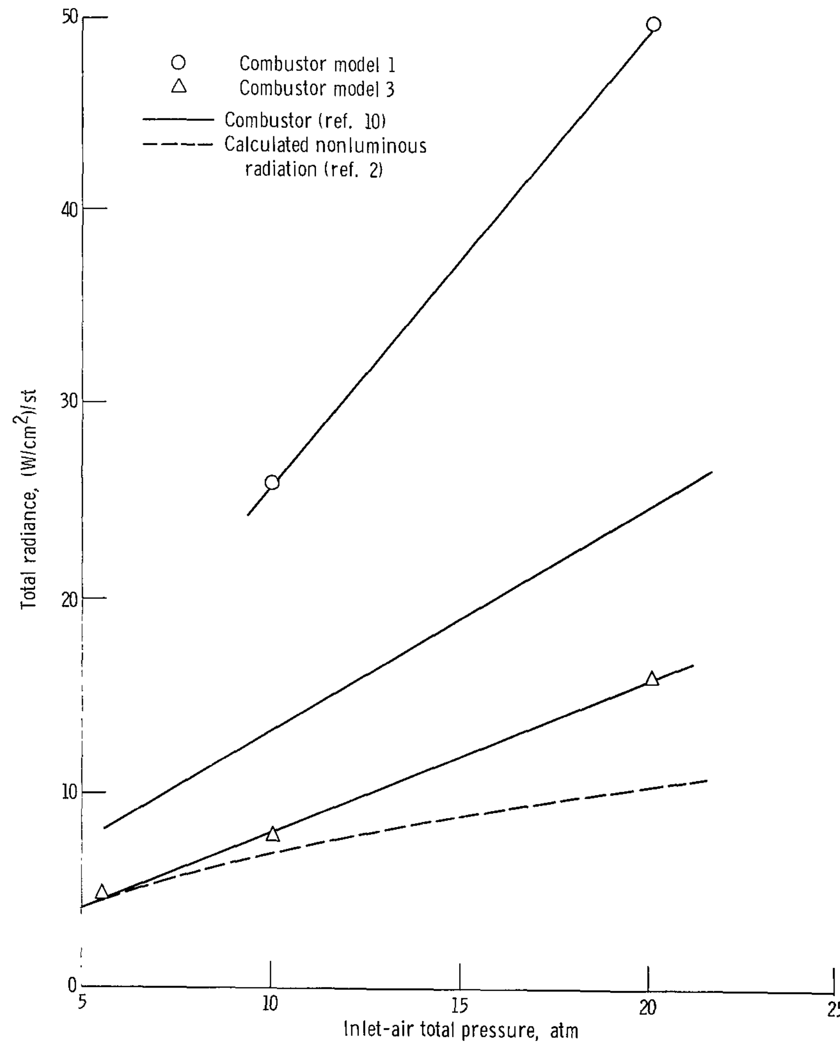


Figure 18. - Effect of inlet-air total pressure on total radiance with combustor models 1 and 3, fixed area fuel nozzles, and type 1 swirlers. Reference velocity, 21.3 meters per second (70 ft/sec); inlet air temperature, 589 K (1060° R); fuel-air ratio, 0.017.

models 1 and 3 operating at an inlet-air pressure of 10 atmospheres. Radiance data were not obtained for the combustor model 2. The total radiance also increased with increasing combustor pressure as shown in figure 18. The total radiance, calculated for nonluminous (low smoke) flames as described in reference 2, and combustor data from reference 10 are included in figure 18 for comparison. Similar effects of pressure on radiance are shown in all cases.

As a result of radiant heat transfer increasing with smoke number, it was found that the combustor liner temperature increased a small amount with increasing combustor pressure as shown in figure 19. This was due to the increase in radiant heat transfer being partially offset by the increase in convective cooling of the liner at higher inlet-air pressures. Good agreement was obtained between calculated and experimental values of liner temperature with combustor model 3.

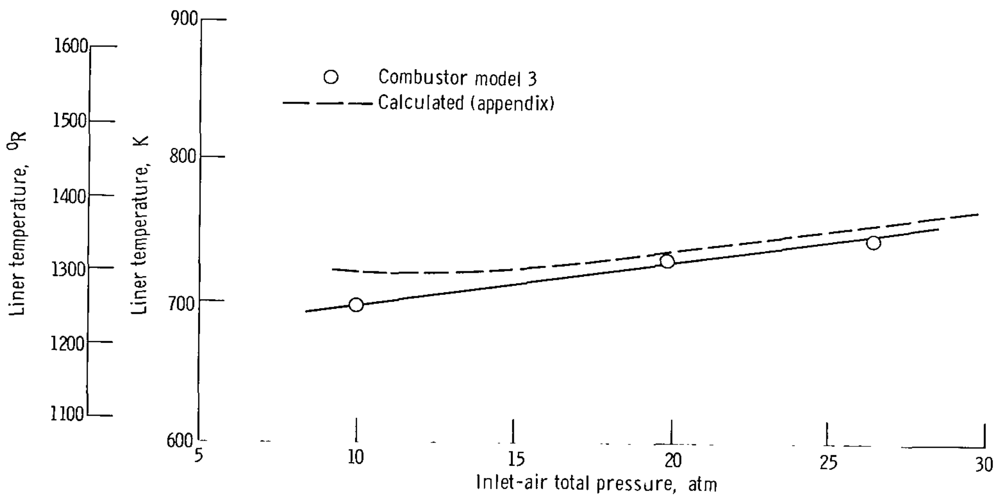


Figure 19. - Effect of inlet-air total pressure on liner temperature with combustor model 3, fixed area fuel nozzles, and type 1 swirlers. Reference velocity, 21.3 meters per second (70 ft/sec); inlet-air total temperature, 589 K (1060° R); fuel-air ratio, 0.019.

In figure 20, the relation between liner temperature and the combustor exit temperature is shown for combustor model 3 at a pressure of 10 atmospheres and inlet-air temperatures of 589 K (1060° R), 755 K (1360° R), and 922 K (1660° R). At 589 K (1060° R), experimental liner temperatures were 10 percent below the calculated values. Comparison of figures 19 and 20 shows that the effect of inlet-air temperature on liner temperature is considerably greater than that of the inlet-air pressure.

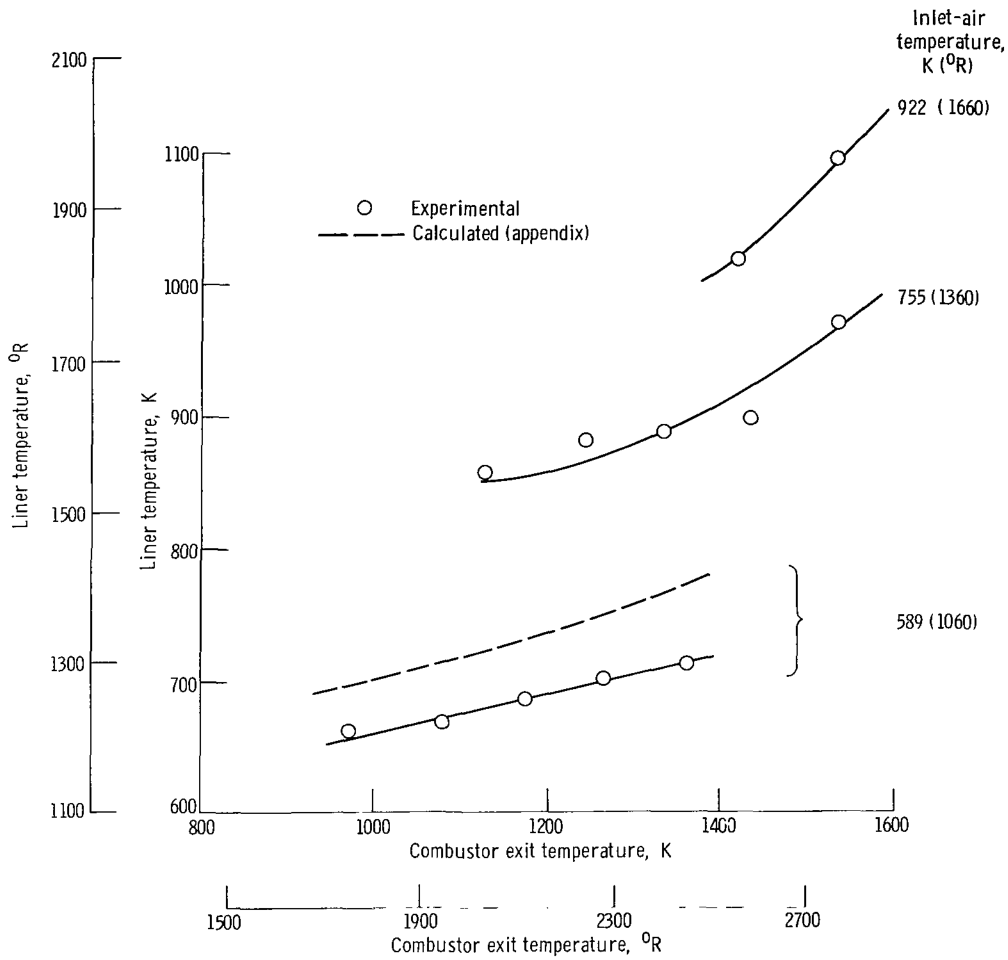
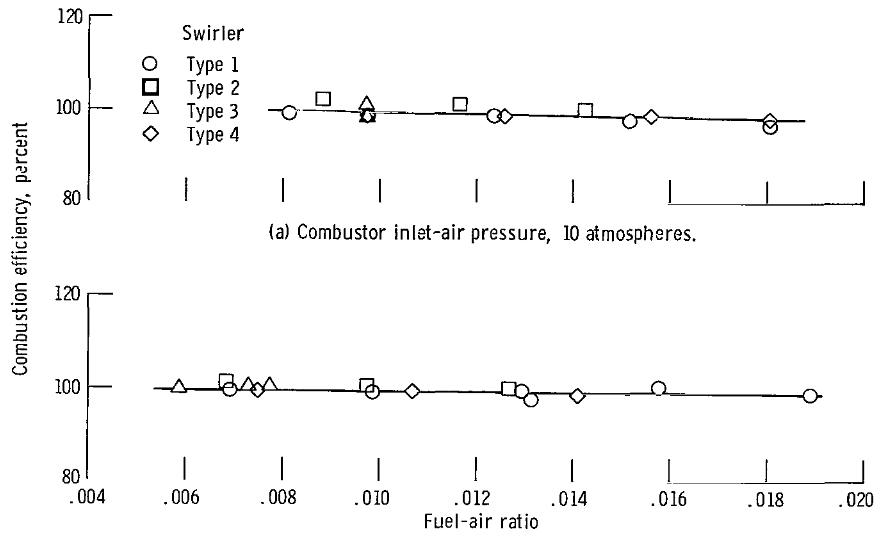


Figure 20. - Relation between combustor exit-air temperature and liner temperature at three inlet-air temperatures. Combustor model 3 with fixed area fuel nozzles and type 1 swirlers. Reference velocity, 21.3 meters per second (70 ft/sec); inlet-air pressure, 10 atmospheres.

Blow-Out Tests

The limiting or minimum inlet-air total pressure at which steady combustion could be maintained in combustor model 3 is shown plotted against reference velocity in figure 21 at a fuel-air ratio of 0.010 and inlet-air total temperatures of 589 K (1060° R), 477 K (860° R), and 355 K (640° R). A minimum inlet-air total pressure of approximately 1.1 atmospheres was required for steady burning at a reference velocity of 21.3 meters per second (70 ft/sec) and an inlet-air temperature of 355 K (640° R). Thus, figure 21 indicates that combustor model 3 did not show as good blow-out or altitude reignition capability as desired. No attempt to improve reignition characteristics was made in this study, and blow-out tests were not made with combustor models 1 or 2.



(b) Combustor inlet-air pressure, 20 atmospheres.

Figure 22. - Combustion efficiency for combustor model 3 with different types of swirlers. Combustor reference velocity, 21.3 meters per second (70 ft/sec); inlet-air temperature, 589 K (1060^{0} R).

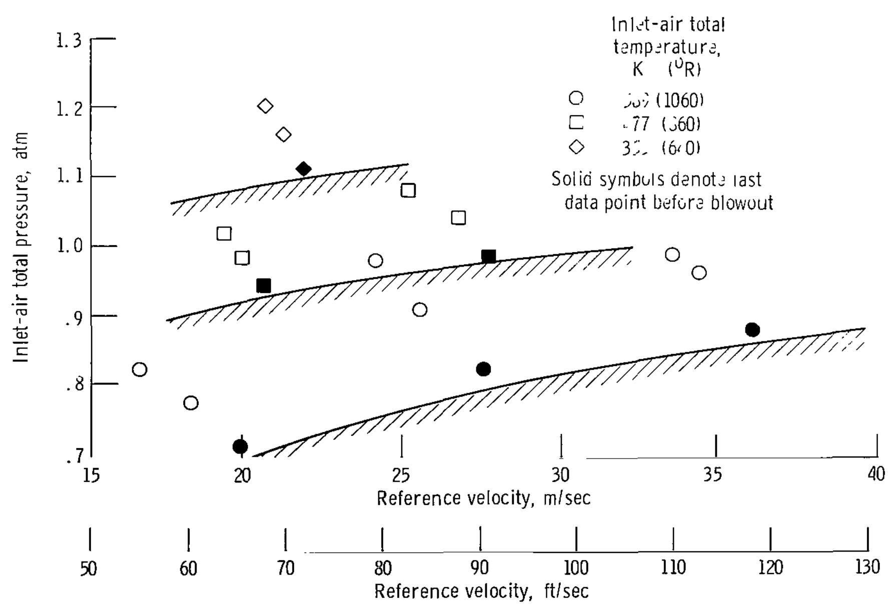


Figure 21. - Combustor blow-out conditions for combustor model 3 with fixed area fuel nozzle, type 1 swirlers, and fuel-air ratio of 0.010.

Comparison of Air Swirlers

The four types of air swirlers shown in figure 4 were tested in the three combustors. Combustor performances were compared by determining: combustion efficiency for combustor model 3, pattern factor for the three combustors, and exhaust smoke number for combustor models 2 and 3.

Combustion efficiency. - As shown in figure 22, combustion efficiencies were approximately 100 percent for all four types of air swirlers with a fuel-air ratio range of 0.006 to 0.019 at inlet-air total pressures of 10 to 20 atmospheres. Thus, all four types of air swirlers gave good combustion efficiencies in combustor model 3.

Pattern factor. - The effect of the dimensionless axial velocity-ratios for the three types of swirler on the pattern factor is shown in figure 23 for the three combustors. In each combustor, the 70° tangential (type 3) swirlers gave the highest velocity ratios and pattern factors. Thus, swirlers with high-velocity ratios were found to give poorer turbulent mixing than low-velocity-ratio swirlers. In all of the combustors axial (types 1 and 2) swirlers with low velocity ratios gave low pattern factors. Pattern factors were best for combustor model 3 using relatively high air flow through low velocity-ratio swirlers and external scoops for secondary-zone mixing. Although the velocity-ratio

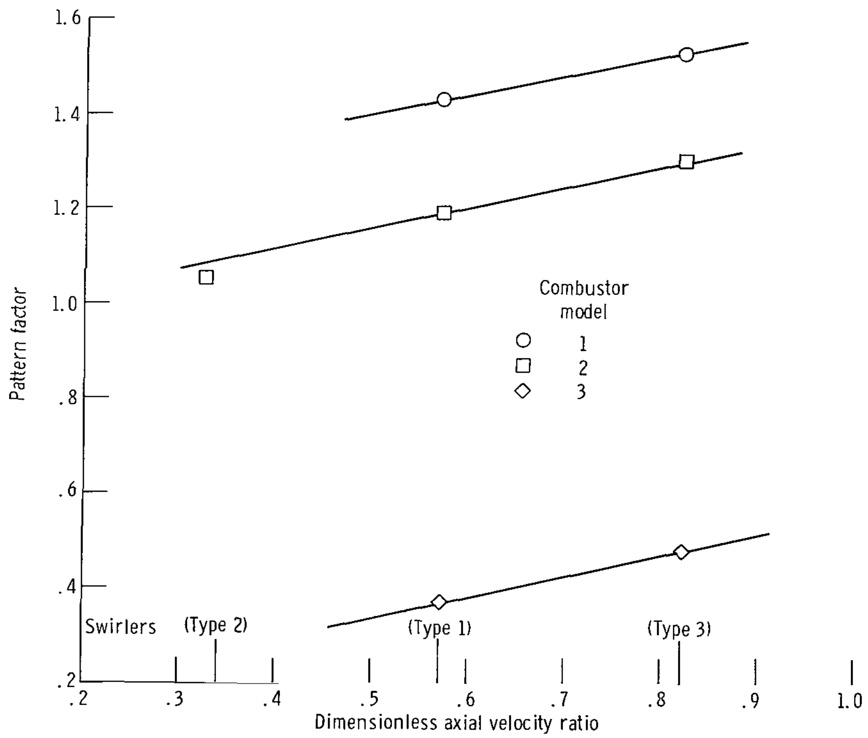


Figure 23. - Relation between dimensionless axial velocity ratio and pattern factor. Combustor reference velocity, 21.3 meters per second (70 ft/sec); inlet air temperature, 589 K (1060° R); fuel-air ratio, 0.013; inlet-air pressure, 10 atmospheres.

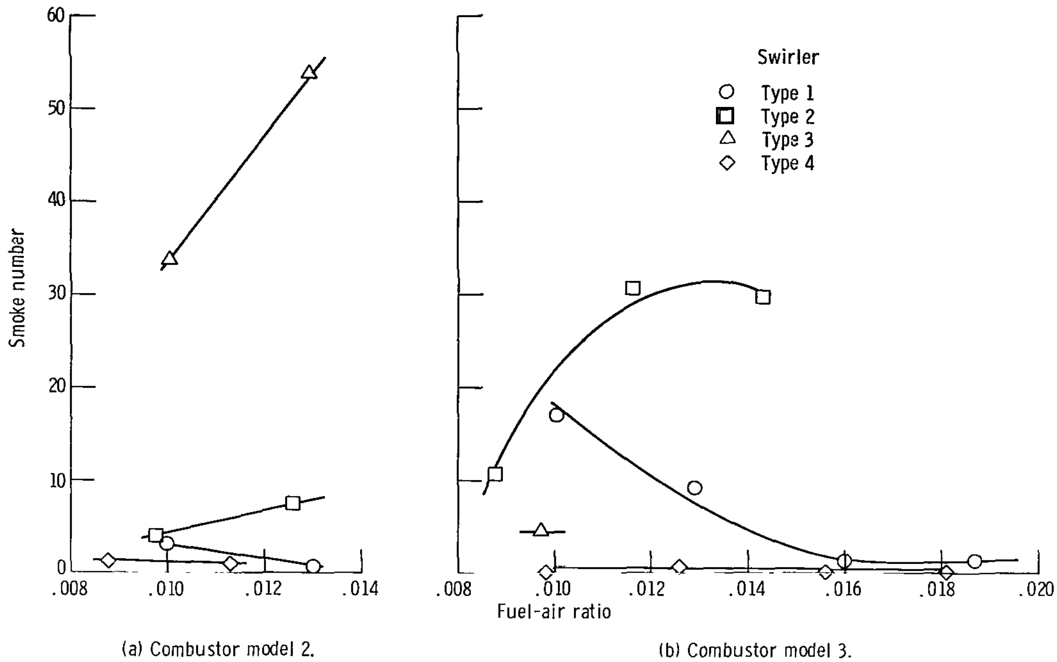


Figure 24. - Smoke number for several swirler types. Combustor reference velocity, 21.3 meters per second (70 ft/sec); inlet-air temperature, 589 K (1060° R); and inlet-air pressure 10 atmospheres.

for the dual-concentric (type 4) swirlers was not calculated directly, it was assumed to be approximately the same as that of the type 2 swirlers.

Exhaust smoke number. - As shown in figure 24, 55° axial (type 1) and dual-concentric (type 4) swirlers had low velocity ratios and gave consistently low exhaust smoke numbers with combustor models 2 and 3 operating at an inlet-air total pressure of 10 atmospheres. Exhaust smoke numbers were very high with the 70° tangential (type 3) swirler in combustor model 2 and fairly high with the 70° axial (type 2) swirler in combustor model 3 at high fuel-air ratios. Thus, low velocity-ratio (type 1 or type 4) swirlers used with combustor model 3 with external scoops gave the lowest smoke formation. This indicated that good primary and secondary-zone mixing was obtained. Exhaust smoke numbers were not obtained for combustor model 1 with type 2, 3, or 4 swirlers.

Additional tests were made with combustor model 3 using variable-area fuel nozzles with type 1 swirlers at pressure drops of 13.6 and 27.2 atmospheres (200 and 400 psia). As shown in figure 25, the variable-area fuel nozzles gave smoke numbers considerably higher than the fixed-orifice fuel nozzles, especially when operating at a high pressure drop. Similar results were obtained with combustor model 1. However, further tests are needed to adequately compare smoking characteristics of fixed- and variable-area fuel nozzles over a wider range of operating conditions.

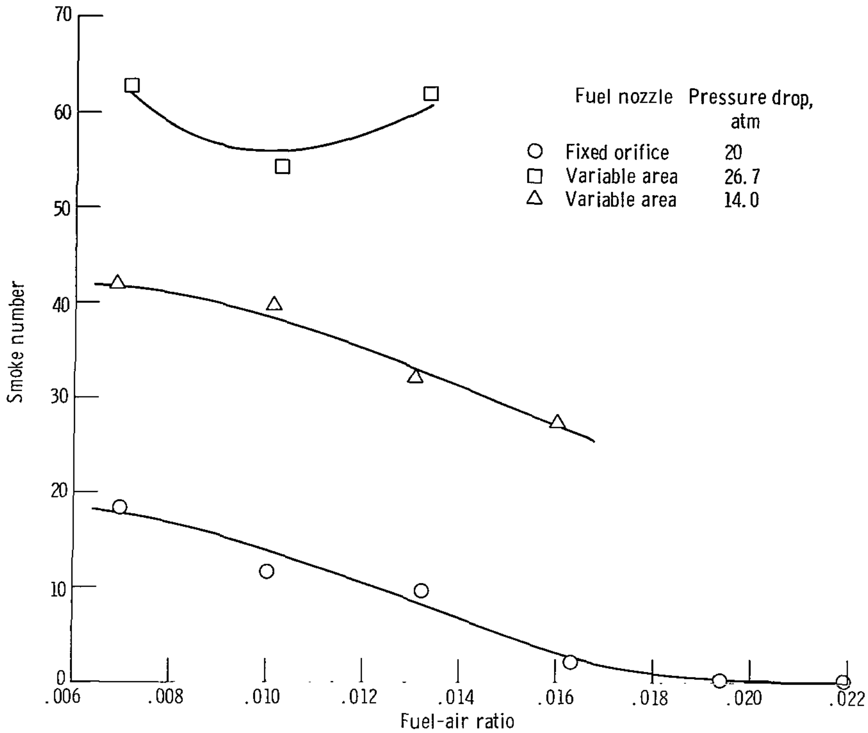


Figure 25. - Comparison of smoke numbers for the combustor model 3 with different types of fuel nozzles. Combustor reference velocity, 21.3 meters per second (70 ft/sec); inlet-air temperature, 589 K (1060° R); inlet-air pressure, 20 atmospheres.

SUMMARY OF RESULTS

Performances were compared for three short-length combustor models and four types of air-swirlers by burning ASTM A-1 fuel at inlet air pressures up to 26.7 atmospheres and determining combustion efficiency, total pressure loss, exit temperature profile, pattern factor, exhaust smoke number, and liner temperature. Test conditions included a fuel-air ratio range of 0.005 to 0.022 at inlet-air total pressures of 10, 20, and 26.7 atmospheres, inlet-air total temperatures of 486 to 756 K (875° to 1360° R) and reference velocities of 16 to 27.4 meters per second (52.5 to 90 ft/sec). The test results were as follows:

1. Combustion efficiencies of nearly 100 percent were obtained for the combustors (models 2 and 3) operating at inlet-air pressures of 10 and 20 atmospheres. Thus, there was no appreciable effect of inlet-air total pressure on combustion efficiency for the range of pressures used in this study.

2. Increasing the open-area of the snout upstream of the swirlers from 20 (combustor model 1) to 40 percent (combustor model 3) produced a small increase in the isothermal total pressure loss: from 3.2 to 4.3 percent at a diffuser inlet Mach number of 0.26 and from 4.4 to 5.8 percent at a 0.35 Mach number.

3. The effect of inlet-air pressure on the exit temperature profile was negligible. As fuel-air ratio increased, the exit temperature profile steadily shifted farther away from the ideal temperature profile.

4. Pattern factors tended to increase with increasing inlet-air pressures at the higher fuel-air ratios and with increasing fuel-air ratios. Also, pattern factors were increased by increasing the dimensionless axial velocity ratio of the swirlers, and were lowest for the combustors with high airflow through the swirlers (models 2 and 3).

5. Exhaust smoke numbers increased with increasing inlet-air total pressures. Exhaust smoke numbers decreased with increasing fuel-air ratios, inlet-air total temperatures, and reference velocities in the case of combustor models 2 and 3. The 55° axial (type 1) and dual-concentric (type 4) swirlers, with relatively low velocity-ratio values, gave consistently low smoke numbers with combustor models 2 and 3. Smoke numbers for the variable-area fuel nozzles were somewhat higher, especially with high pressure drops across the nozzles.

6. Combustor liner temperature increased to a small degree with inlet-air pressure but rapidly with increasing inlet-air total temperature. The former affect was attributed to increased radiant heat-transfer rates, resulting from increased smoke formation at elevated combustor pressures, which were partially compensated for by increased convective cooling rates.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 14, 1971,
720-03.

APPENDIX - LINER TEMPERATURE CALCULATIONS

The following steady-state heat balance was written at the liner wall to determine the adiabatic liner temperature:

$$\left(q_r + q_c\right)_{in} = \left(q_r' + q_c'\right)_{out} \tag{A1}$$

where q_r is the net rate of radiant heat transfer from the flame to the liner, q_c is the net rate of convective heat transfer from the combustion gases to the liner, q_r' is the net rate of radiant heat transfer from the liner to the combustor wall, and q_c' is the net rate of convective heat transfer from the liner to the cooling air stream.

Values of q_r were determined from the expression

$$q_r = \sigma\epsilon\left(T_f^4 - T_w^4\right) \tag{A2}$$

where σ is the Stefan-Boltzmann constant, ϵ and T_f are the flame emissivity and temperature, respectively, which were determined experimentally from radiometric measurements (ref. 2), and T_w is the adiabatic liner temperature. Emissivity and absorptivity were assumed equal at both flame and wall temperatures.

Values of q_c were determined from the expression

$$q_c = h_1(T_{ad} - T_w) \tag{A3}$$

where the heat-transfer coefficient h_1 was evaluated from the expression $Nu_X = 0.037\ Re_X^{0.8} Pr^{0.33}$ which correlates the Nusselt number Nu_X with the Reynolds and Prandtl numbers Re_X and Pr, respectively, as given in reference 11 for a flat plate with longitudinal flow. The adiabatic gas temperature T_{ad} was calculated using the following expression for film cooling effectiveness τ as described in reference 12:

$$\tau = \frac{T_f - T_{ad}}{T_f - T_a} = \frac{1}{1 + K\dfrac{\dot{m}_f X}{\dot{m}_c H}} \tag{A4}$$

where T_f and T_a are the hot gas and coolant air temperatures, respectively, $\dot{m}_f$ is the mass flow rate in the flame zone, $\dot{m}_c$ is the coolant mass flow rate, H is the primary flame zone duct height, K is a mixing coefficient (assumed to be 0.03), and X is the downstream distance from the slot exit.

Values of q_r' were determined from the expression

$$q_r' = \sigma\left[\frac{\epsilon_w\epsilon_c}{\epsilon_w\epsilon_c\left(\frac{1}{F_{wc}} - 1\right) + \epsilon_c + \epsilon_w(1 - \epsilon_c)}\right]\left(T_w^4 - T_c^4\right) \tag{A5}$$

where ϵ_w and ϵ_c are the emissivity of the liner and combustor wall, respectively, T_c is the combustor wall temperature, and F_{wc} is the radiation interchange factor between the liner and combustor wall.

Values of q_c' were determined from the expression

$$q_c' = h_2(T_w - T_a) \tag{A6}$$

where the heat-transfer coefficient h_2 was evaluated as described for h_1, and T_a is the inlet air temperature. Thus, the liner temperature T_w was obtained by substituting equations (A2), (A3), (A5), and (A6) into equation (A1) and solving for the adiabatic liner temperature.

In order to compare calculated values with experimental values of the adiabatic liner temperature, the following factors were considered in correcting the thermocouple measurements: (1) the temperature gradient due to the thickness of the liner, (2) the heat loss in the thermocouple wires, and (3) the additional cooling affect of the fins which supported the liner in the cooling air stream. Over the range of operating conditions, corrections for thermocouples measurements ranged from (1) 5 to 25 K (9° to 45° R) for the temperature gradient correction, (2) 4 to 8 K (7° to 15° R) for heat loss in the thermocouple wire, and (3) 17 to 51 K (30° to 91° R) for the cooling affect of the fins.

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